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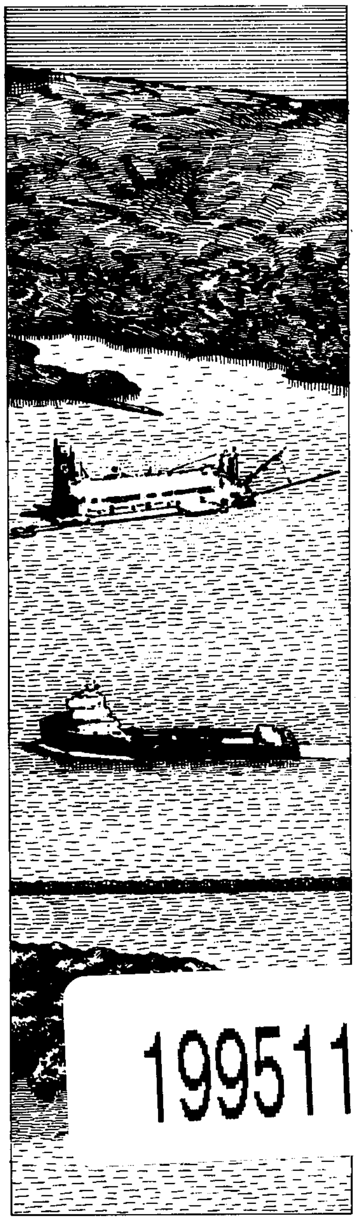



DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-95-7

# MATERIAL PROPERTIES RELATED TO NAVIGATION AND DREDGING: SUMMARY REPORT FOR TECHNICAL AREA 2

compiled by

Lyndell Z. Hales

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199



September 1995

Final Report

Approved For Public Release; Distribution Is Unlimited

Prepared for DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 32492

The Dredging Research Program (DRP) is a seven-year program of the U.S. Army Corps of Engineers. DRP research is managed in these five technical areas:

Area 1 - Analysis of Dredged Material Placed in Open Water
Area 2 - Material Properties Related to Navigation and Dredging
Area 3 - Dredge Plant Equipment and Systems Processes
Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
Area 5 - Management of Dredging Projects



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US Army Corps of Engineers
Waterways Experiment Station

# Dredging Research Program Report Summary

## *Material Properties Related to Navigation and Dredging: Summary Report for Technical Area 2 (TR DRP-95-7)*

**ISSUE:** The navigation mission of the Corps of Engineers entails maintenance dredging of about 40,000 km of navigable channels at an annual cost of about $400 million. Deficiencies in the dredging program have been documented by the Corps field operating Division and District offices. Implementation of the Dredging Research Program (DRP) to meet demands of changing conditions related to dredging activities, and the generation of significant technology that will be adopted by all dredging interests, are means to reduce the cost of dredging the Nation's waterways and harbors and save taxpayer dollars.

**RESEARCH:** Investigations under DRP Technical Area 2, "Material Properties Related to Navigation and Dredging," developed descriptors for bottom sediments to be dredged, devised new drilling parameter recorder technology, designed and field-tested a methodology for surveying navigation channels containing fluid mud, and developed acoustic impedance techniques for performing rapid measurements of characteristics of consolidated sediments.

**SUMMARY:** A geotechnical site-investigation strategy for dredging projects was developed and descriptors were proposed so that engineering properties of bottom sediments could be readily inferred. A drilling parameter recorder and a point load test were developed to reflect operation of a drill rig and characteristics of the formation being drilled. An instrumented towed sled was fabricated which will ride automatically in a channel of fluid mud at the level being defined as navigable, thus serving as prima facie evidence of the navigability of the material. A waterborne seismic acoustic impedance system was developed to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging.

**AVAILABILITY OF REPORT:** The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service report numbers may be requested from WES Librarians. To purchase a copy of the report, call NTIS at (703) 487-4780.

**About the Author:** Dr. Lyndell Z. Hales is Assistant Manager of the Dredging Research Program (DRP), managed by the Coastal Engineering Research Center at the U.S. Army Engineer Waterways Experiment Station. For further information about the DRP, contact Mr. E. Clark McNair, Jr., Manager, DRP, at (601) 634-2070.

**Dredging Research Program**

Technical Report DRP-95-7
September 1995

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compiled by Lyndell Z. Hales

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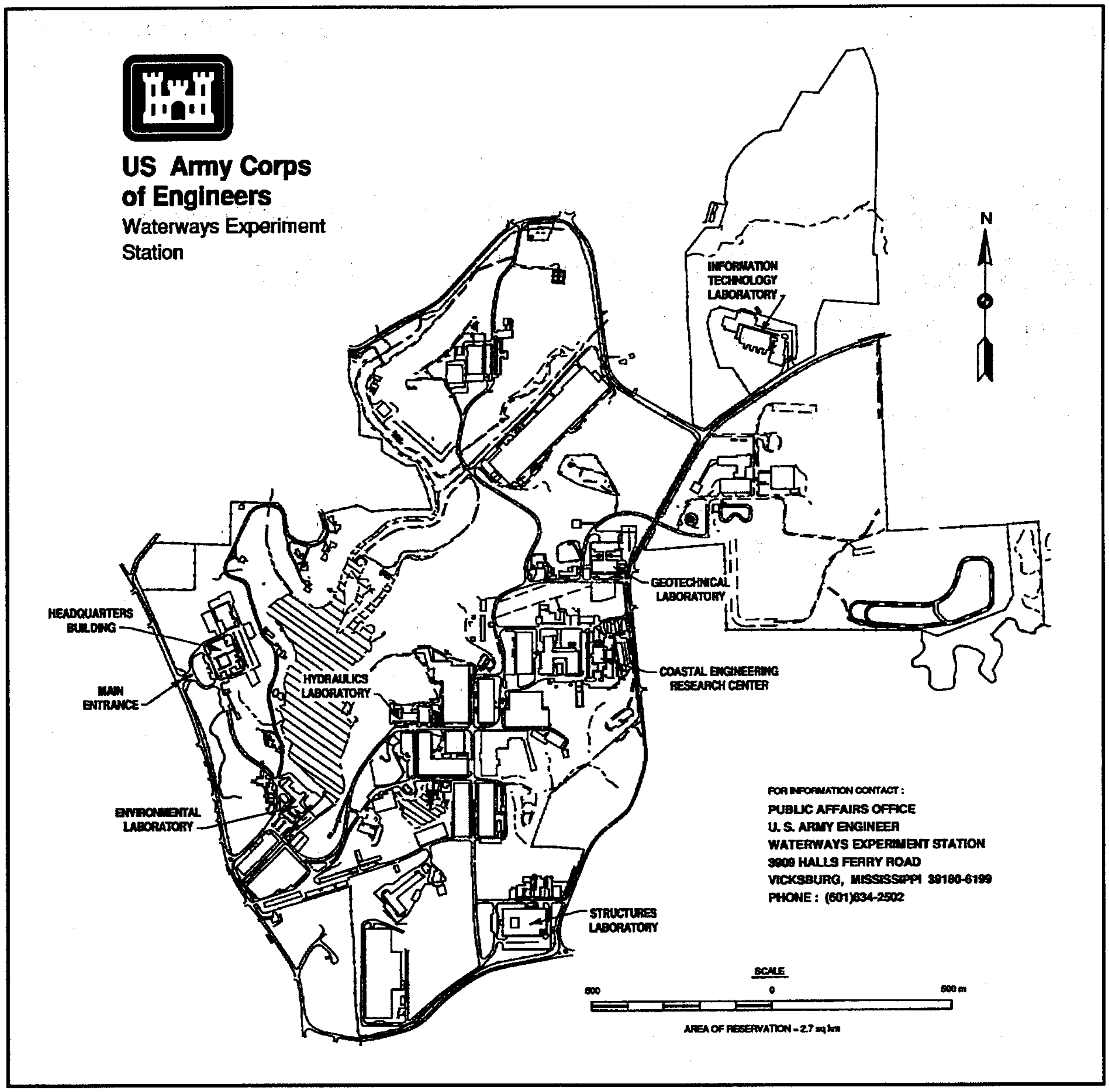


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# Preface

This report summarizes research by U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program (DRP) Technical Area 2, "Material Properties Related to Navigation and Dredging." The DRP was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Technical Monitors for Technical Area 2 were Messrs. Barry W. Holliday, David A. Roellig (retired), and John Sanda, HQUSACE. Chief Technical Monitor was Mr. Robert H. Campbell (retired), HQUSACE.

This summary report was compiled by Dr. Lyndell Z. Hales, Coastal Engineering Research Center (CERC), WES, and was extracted essentially verbatim from Technical Area 2 reports.

Technical Area 2 studies were conducted by or under the following WES supervision:

Geotechnical Laboratory (GL)—Dr. Jack Fowler (retired), Principal Investigator, Soil Mechanics Branch (SMB), Soil and Rock Mechanics Division (S&RMD); Mr. Hardy J. Smith, Principal Investigator, Rock Mechanics Branch (RMB), S&RMD; and Dr. Robert F. Ballard, Jr., Principal Investigator, Earthquake Engineering and Geophysics Division (EE&GD). Additional supervision was provided by Mr. G. B. Mitchell (deceased), former Chief, SMB; Mr. William M. Myers, Chief, SMB; Mr. Jerry S. Huie, Chief, RMB; Dr. Don C. Banks, Chief, S&RMD; Dr. Arley G. Franklin, Chief, EE&GD; Dr. Paul F. Hadala (retired), Assistant Director, GL; and Dr. William F. Marcuson III, Director, GL.

Hydraulics Laboratory (HL)—Mr. Allen M. Teeter, Principal Investigator, Estuarine Processes Branch (EPB), Estuaries Division (ED); Mr. Richard G. McGee, Hydraulic Analysis Branch (HAB), Hydraulic Structures Division (HSD); Mr. Michael P. Alexander, Estuarine Engineering Branch (EEB), ED; and Mr. Glynn E. Banks, EEB. Additional supervision was provided by Mr. William D. Martin, Chief, EEB; Dr. Bobby J. Brown (retired), Chief, HAB; Mr. William H. McAnally, Jr., Chief, ED; Mr. Glenn A. Pickering (retired), Chief, HSD; Mr. Richard A. Sager, Assistant Director, HL; and Mr. Frank A. Herrmann, Jr. (retired), Director, HL.

Dr. Banks and Mr. Smith were the Technical Area Managers for Technical Area 2.

Mr. E. Clark McNair, Jr., CERC, and Dr. Hales were Manager and Assistant Manager, respectively, of the DRP. Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., were Director and Assistant Director, respectively, of CERC, which conducted the DRP.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

For further information on this report or on the Dredging Research Program, please contact Mr. E. Clark McNair, Jr., DRP Program Manager, WES, at (601) 634-2070.

# Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| cubic feet | 0.02832 | cubic metres |
| cubic yards | 0.7645549 | cubic metres |
| cubic yards per hour | 0.7645549 | cubic metres per hour |
| feet | 0.3048 | metres |
| feet per hour | 0.00847 | centimetres per second |
| feet per minute | 0.005080 | metres per second |
| feet per second | 0.3048 | metres per second |
| foot-pounds (force) | 1.355818 | metre-newtons or joules |
| inches | 2.54 | centimetres |
| pounds (force) | 4.448222 | newtons |
| pounds (force) per square inch | 6.894757 | kilopascals |
| pounds (force) per foot | 14.89501 | grams per centimetre |
| square feet | 0.09290 | square metres |
| tons (force) per square foot | 9,773.6 | kilograms per square metre |

# Summary

This report summarizes research conducted under the Dredging Research Program (DRP) Technical Area 2, "Material Properties Related to Navigation and Dredging," at the U.S. Army Engineer Waterways Experiment Station. The purpose of this research was to develop new instrumentation and technology for more thorough subsurface investigations at dredging projects and to refine descriptors for better communicating of knowledge from Corps geotechnical engineers to dredging contractors. These DRP products will provide more comprehensive understanding of subbottom characteristics and will reduce the impact of contractor claims regarding differing and changed site conditions. Technical Area 2 was comprised of the following four specific research topics.

"Descriptors for Bottom Sediments to be Dredged" provided a geotechnical site investigation strategy for dredging projects and developed descriptors such that engineering properties of bottom and subbottom sediments are either directly given or can be readily inferred for engineering applications such as dredgeability predictions. A knowledge-based expert system was developed consisting of two modules (GEOSITE and DREDGABL) to provide access to recorded expertise and guidance from experts in their respective fields, for use by project planners, geotechnical engineers, and dredging estimators.

"Descriptors for Rock Material to be Dredged" developed a drilling parameter recorder (DPR) and a point-load test (PLT) compressive strength indicator. The DPR is a data-acquisition system for roller-bit drilling that monitors, measures, and records various physical parameters that reflect the operation of the drill rig, thereby producing a record of the characteristics of the formation being drilled. Calibration of DPR roller-bit holes with only a minimal number of cored drill holes will significantly reduce the cost of subsurface exploration. The PLT was developed to correlate weak saturated rock with unconfined compressive strength, and a point-load index and unconfined compressive strength (PLUCS) database system were created to store, retrieve, and compare weak saturated rock test data.

"Measurement and Definition of Navigable Depth in Fluff and Fluid Mud" developed a fluid-mud surveying system that integrates an instrumented towed sled, a conventional dual-frequency acoustic depth sounder, and hydrographic survey positioning-control and logging components. Many navigation channels

contain thick layers of fluid mud that impede navigation and restrict use of conventional acoustic methods of surveying. The towed sled will furrow into the fluid mud and ride automatically at the level being defined as navigable, thus serving as prima facie evidence of the navigability of the material.

"Rapid Measurements of Properties of Consolidated Sediments" produced instrumentation and techniques to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. This waterborne seismic acoustic impedance (AI) system developed an electronic package to send and analyze acoustic signals to provide geophysical information such as density, shear strength, and grain size from the acoustic-reflectivity strength of the signals and thus comprehensive subbottom data.

# 1 Introduction

The U.S. Army Corps of Engineers is involved in virtually every navigation dredging operation performed in the United States. The Corps' navigation mission entails maintenance and improvement of about 40,000 km of navigable channels serving about 400 ports, including 130 of the Nation's 150 largest cities. Dredging is a significant method for achieving the Corps' navigation mission. The Corps dredges an average annual 230 million cu m of sedimentary material at an annual cost of about $400 million. The Corps also supports the U.S. Navy's maintenance and new-work dredging program (McNair 1989).

## Background

### Genesis of the Dredging Research Program

Significant changes occurred in the conduct of U.S. dredging operations and the coordination of such dredging with environmental protection agencies as a result of the National Environmental Policy Act of 1969. Subsequent Federal legislation authorized a study of the ability of private contractors to perform the Nation's required navigation dredging activities. That study determined that, from national emergency considerations, only a minimal Federal dredge fleet was necessary, and the bulk of hopper-dredge activities shifted from the once large Corps fleet to private sector contract hopper dredges (Hales 1995).

A long period in which Corps' dredging activities consisted almost totally of maintaining existing waterways and harbors changed with passage of the Water Resources Development Act of 1986. This legislation authorized major deepening and widening of existing navigation projects to accommodate modern Navy and merchant vessels. Future changes in dredging are not expected to be any less dramatic than those which occurred in recent years. The Corps will continue to be challenged in pursuing optimal means of performing its dredging activities. Implementation of an applied research and development program to meet demands of changing conditions related to Corps dredging activities and the generation of significant technology that will be adopted by all dredging interests are means of reducing the cost of dredging the Nation's waterways and harbors.

## Dredging Research Program

The concept of the Dredging Research Program (DRP) emerged from leadership of Corps of Engineers Headquarters (Navigation and Dredging Division and Directorate of Research and Development (CERD)) in the mid-1980s (McNair 1988). It was realized early in the program development that research should be directed toward addressing documented deficiencies identified by the primary Corps users, namely the field operating Division and District offices. Problems identified by the field offices were formulated into specific applied research work tasks describing objectives, research methodologies, user products, and time/cost schedules. CERD delegated primary responsibility for developing the DRP to the U.S. Army Engineer Waterways Experiment Station (WES). The 7-year, $35-million DRP, initiated in FY88, achieved all major milestones, goals, and objectives scheduled in the program-planning process.

A major DRP objective was the development of equipment, instrumentation, software, and operational monitoring and management procedures to reduce the cost of dredging the Nation's waterways and harbors to a minimum consistent with Corps mission requirements and environmental responsibility. The DRP consisted of five technical areas from which many distinct products were generated and annual and one-time direct and indirect benefits were quantifiable.

*a.* *Technical Area 1.* Analysis of Dredged Materials Disposed in Open Water.

*b.* *Technical Area 2.* Material Properties Related to Navigation and Dredging.

*c.* *Technical Area 3.* Dredge Plant Equipment and Systems Processes.

*d.* *Technical Area 4.* Vessel Positioning, Survey Controls, and Dredge Monitoring Systems.

*e.* *Technical Area 5.* Management of Dredging Projects.

## Technical Area 2

Objectives of Technical Area 2, "Material Properties Related to Navigation and Dredging," included development of (a) descriptors for bottom sediments to be dredged, (b) new drilling parameter recorder technology, (c) methodology for surveying in fluid mud, and (d) an acoustic impedance technique for performing rapid measurements of consolidated sediments. Technical Area 2 research areas included:

*a.* Descriptors for bottom sediments to be dredged.

*b.* Descriptors for rock material to be dredged.

*c.* Measurement and definition of navigable depth in fluff and fluid mud.

*d.* Rapid measurements of properties of consolidated sediments.

## Report Organization

Chapter 2 of this summary report of Technical Area 2 presents (a) a geotechnical site-investigation strategy for dredging projects; (b) geotechnical factors in the dredgeability of sediments and the resulting descriptors for sediments to be dredged; (c) guidance in the geotechnical evaluation of the dredgeability of sediments using a knowledge-based expert system GEODREDG that contains two subsystems, DREDGABL and GEOSITE; and (d) geotechnical engineering knowledge gained from DRP research as applicable to reducing contract claims of changed conditions at dredging sites.

Chapter 3 describes new technology developed by the DRP to enhance the ability of the Corps to obtain more precise and comprehensive geotechnical data about proposed dredging projects to minimize the impact of contractor claims of differing site conditions, with particular reference to new-work rock dredging. Two of these enhanced geotechnical devices are the drilling parameter recorder (DPR) and the point load test (PLT).

Chapter 4 presents the development of a survey tool (towed sled for fluid-mud channel surveys) to determine navigable depth in areas where fluid mud obscures the bottom to conventional acoustic methods such as the fathometer. Benefits of the towed sled include improved efficiency in maintenance operations through better definition of what areas actually require dredging or have been sufficiently dredged, establishing more meaningful dredging priorities, and scheduling dredging cycles.

Chapter 5 discusses the development of a technique to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. A digital data-acquisition system was combined with specialized processing software to accurately assess bottom and subbottom conditions in situ, which resulted in a waterborne seismic acoustic impedance (AI) technique for subbottom imaging.

Chapter 6 is a synopsis of technical reports pertaining to products and technology developed under the DRP to better understand material properties related to navigation and dredging; the prime objective of Technical Area 2.

# 2 Descriptors for Bottom Sediments to be Dredged

The methods of observation and the descriptors currently being used to characterize bottom sediments to be dredged represent a mixture adopted (sometimes not adapted) from diverse fields such as environmental engineering, geology, soil mechanics, and foundation engineering. Descriptors needed to be developed such that engineering properties are either directly given or can be readily inferred for engineering applications such as dredgeability prediction (Calhoun et al. 1986). The term 'dredgeability' is taken to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in situ material characteristics.

## Geotechnical Site-Investigation Strategy for Dredging Projects[1]

The objective of a geotechnical site investigation for a dredging project is to obtain the most complete and accurate estimate of the location and character of the materials to be dredged that is possible within the limits of available time, money, and practicality. This information must then be communicated in a readily understood manner to all persons involved in the design, cost estimation, and construction of the project. A site investigation for dredging consists of studies of all available existing information augmented by geophysical and geotechnical subbottom investigations, including the sampling and testing of soils. Data are summarized in a predicted geotechnical subbottom profile. The validity of the predicted profile is dependent on the type and amount of site investigation and on the knowledge and skill of the interpreter(s) of the data.

Bids submitted on a project are affected by the monetary risks the contractors are willing to take after considering their uncertainty about the character and location of the materials to be dredged. The greater the risk from

[1] This section of Chapter 2 was extracted from Spigolon (1993b,c).

incomplete information, the greater that part of the bid price that considers the risk. If unforeseen adverse site conditions are encountered, the contractor may file a claim for changed conditions. Therefore, the amount to be spent on a site investigation by the owner is directly related to the amount that the bid price and the total cost involved in processing claims for changed conditions can be reduced by the availability of a more comprehensive geotechnical site description.

## Factors affecting a site-investigation strategy

The strategy or plan for a geotechnical subbottom investigation must consider three general factors that establish the necessary scope of the study: (a) variability of the natural soil deposits, (b) size of the sampling and testing program, and (c) the value of additional information.

**Variability of natural soil deposits**. A single homogeneous soil deposit for a single property (e.g., shear strength) is most effectively characterized by defining the trend line of local average values and the variability of individual test values about that trend line. Variability in the measured test results from the average stems from three causes: (a) natural variations in the composition of the material, (b) natural variations in the deposition process, and (c) variations due to the sampling and testing process.

**Size of sampling and testing program**. The amount of information needed to reduce uncertainty in site characterization to an acceptable level is a function of the complexity of the soil deposits at the site. If the entire project consisted of one soil type with a uniform set of properties and no variation with distance, then only one sample would need to be tested. As site characteristics become more complex, the amount of site-investigation effort (i.e., the number of borings and samples) needed to reduce uncertainty increases. There is a maximum to the curve of amount of site-investigation effort that is useful versus complexity of site properties. If the site is highly complex and heterogeneous, the amount of necessary site-investigation effort drops because no reasonable amount of site exploration can characterize the site adequately. In that case, there need only be sufficient site-investigation effort to establish, to a reasonable level of certainty, that the site is highly complex. The dredging contractor's bid amount will be increased accordingly.

**Value of additional information**. In preparing a bid, the dredging contractor is faced with risks from a number of unknowns, including weather, personnel, and equipment. The risk factors also include geotechnical risk (i.e., soil types to be encountered, difficulty of dredging them, cost of mobilization of the wrong equipment for the soil types, and cost of pursuing a claim of changed conditions). Hence, all contractors must include in their bid price a cost of anticipated risk, including the geotechnical risk.

If a dredging project is offered for bid with only minimal geotechnical knowledge available, then a cost associated with geotechnical risk will be part

of the total project cost as reflected in the bid price. Alternatively, assume that a very extensive geotechnical site investigation has been made; so extensive that the knowledge of the soil profile could be called perfect. The contractor now has all knowledge beforehand needed to match equipment to soil type and character; to schedule equipment; and to determine fuel, personnel, and wear costs. There is absolutely no risk in the project due to lack of knowledge of the characteristics of the soils in the dredging prism. This savings in bid price is the value of perfect information and represents an upper limit of project savings due to the availability of complete geotechnical information.

If the cost of obtaining geotechnical site information is a linear function of the value of that information, then the optimum level of site investigation occurs where the cost of obtaining the geotechnical information curve intersects the value of sample information curve on a plot of project cost versus amount of pertinent information.

## Dredgeability properties of soil sediments

Soil sediments have different dredgeability properties during the three distinct stages of a dredging project (excavation, removal and transport, and disposal). Dredgeability properties for each stage of the operation include:

*a. Excavation stage.*

(1) **Suctionability**. Facility with which a sediment can be excavated by plain suction (the sediment is drawn into a hydraulic pipe at or very near its in situ density, i.e., with little or no diluting water).

(2) **Erodibility (scourability)**. Ease with which a sediment can be excavated by shearing or direct impact of a fluid moving parallel or at an angle to the sediment surface.

(3) **Cuttability**. Relative ease with which a sediment can be excavated by a blade, knife, or plow. Properties that govern cuttability include shear strength, grain-size distribution (percent fines), plasticity, and adhesion to the metal cutting surface.

(4) **Scoopability (digability)**. Ease with which a sediment can be excavated or dislodged using the cutting edge of a scoop, bucket, or shovel.

(5) **Flowability (slope instability)**. Facility of a sloped soil deposit to fail and flow into an excavation at its lowest end, the instability of a sloped soil.

*b. Removal and transport stage.*

(1) **Pumpability**. Ease with which a soil slurry can be pumped in a pipeline. Sediment type is only one of the factors influencing the energy needed for pipeline transport of sediments. The required energy depends on the typical grain size of the sediment, defined as $d_{50}$ by Herbich (1992). Greatest slurry fluidity occurs with rounded grains.

(2) **Sedimentation rate**. Rate at which a particle will settle in still water, such as within a dump scow, is a function of grain diameter and the viscosity of the fluid. Assessment of settleability requires knowledge of grain-size distribution (percent silt and percent clay), plasticity of the fines, and salinity of the water.

(3) **Bulking factor of redeposited soils**. Ratio of the volume occupied by a given amount of soil in a dump scow immediately after deposition by a dredging process, to the volume occupied by the same amount of soil in situ. Deposition volume of a soil is not constant but depends on grain-size distribution, flocculation capacity, percentage of fines (silt and clay), and plasticity.

*c. Disposal stage.*

(1) **Dumpability**. Cohesive soils that have a medium to high plasticity index (PI) may adhere to the barge or other equipment during disposal. Granular soils containing fines may bridge and require jetting with high-pressure water streams.

(2) **Sedimentation rate**. Rate at which a particle will settle in still water, such as within a disposal site, a function of grain diameter; larger particles settle faster. Silt and clay particles take hours or days to settle through the water column.

(3) **Compactability**. Machine compaction to a specification limit in a land disposal area requires either granular soil or low-plasticity cohesive soil that has dried to approximately the plastic limit water content. All soils at almost any water content can be densified mechanically, but not to specified limits.

## Procedure for a geotechnical site investigation

A geotechnical site investigation for a dredging project must answer several questions:

*a.* How many different soil and rock deposits are there within the proposed dredging prism? Where are they located and what is their configuration?

*b.* What kind of material constitutes each deposit? Which geotechnical properties will characterize each soil deposit? What are the average values and the ranges in values of each characteristic property?

*c.* Are the deposits homogeneous, heterogeneous, or do the properties trend in a known or predictable manner?

**Site-investigation procedure**. The procedure for a typical geotechnical site investigation for a dredging project contains the following steps:

*a.* A review is made of all available pertinent information.

*b.* Based on prior information, an initial hypothesis of the geotechnical subbottom profile is developed, including the types, configuration, and geotechnical character of the subbottom soils present.

*c.* If the available information is sufficient for the project, the site investigation is terminated. If not, then an estimate is made of site variability. If the site variability is not well-known, then a geophysical survey may be appropriate.

*d.* Where appropriate, continuous subbottom information is obtained by geophysical studies using acoustic subbottom profiling or other suitable methods. Ground-truth correlation is required.

*e.* If the updated geotechnical information is now sufficient for the project, the site investigation is terminated.

*f.* If the amended subsurface profile estimate is still not sufficient, then a geotechnical physical site-exploration plan is formulated. Number and location of the test sites will be dictated by site variability.

*g.* At each test site, specific depths and methods are selected for sampling and testing the subbottom materials. Sampling depth may be reached by drilling or digging pits. A description and classification are made for each sample.

*h.* The new geotechnical information is summarized and reviewed for consistency with the previous profile estimate.

*i.* If the revised subbottom profile estimate is now sufficient for the project, the site investigation is terminated. However, if more information is required, then additional geophysical and/or geotechnical sampling and testing are done. This iteration is continued until a point of sufficiency is reached.

**Geophysical investigation methods**. Using direct contact with the soil deposit at various points, a large mass of soil can be investigated using electrical, acoustical, or seismic waves transmitted through the mass. Geophysical

methods are indirect and nonintrusive and are generally characterized by large-scale measurements that produce an averaging of the soil properties over the zone of test influence. Such methods do not include the capability of obtaining or testing a specific sample.

The distinguishing character of all geophysical methods is the ability to provide a continuous soil profile with only a few general soil characteristics indicated. These methods require extensive calibration usually with ground-truth studies of the in situ project soils. Ground-truth tests indicate only the characteristics of the soils in the immediate location of the boring or pit. Extrapolation of the data between borings or pits requires considerable interpretation of all other available data. Stratification that may be inferred from one boring or a group of borings may not be valid because of discontinuities or inclusions that have been missed. Drilling and profiling are complementary in many ways. The strength of one is the weakness of the other and vice versa. Most available geophysical systems can be operated from a vessel, many while the vessel is moving.

### Sampling underwater soils

Three terms regarding soil sampling deserve strict definition: in situ, undisturbed sample, and representative sample. In situ derives from the Latin expression translated as "at the site" and is generally used to indicate the condition of a soil as it exists in its naturally placed location before intervention by man or machine. A truly undisturbed sample is one that maintains all of the in situ soil mass characteristics (including shape; volume; pore pressure; and grain size, orientation, and structure) and the in situ horizontal and vertical pressures. In reality, a so-called undisturbed sample cannot completely retain all of these attributes. A representative sample may be remolded slightly or completely; i.e., it contains all of the soil materials, both solids and fluids, of its in situ state but does not maintain the structure, grain orientation, or in situ density. Such samples are appropriate for soil material property tests but not for soil mass properties tests. Laboratory strength tests of clays are heavily dependent on undisturbed sampling.

### Implementing a site-investigation strategy

The practical development and implementation of a site-investigation strategy for a dredging site involves making decisions to answer a number of specific questions.

*a.* What should the scope of the investigation be?

(1) Is existing information about the subsurface condition at the site sufficient?

(2) Will a geophysical exploration be useful?

(3) Is sampling and/or testing at field exploration sites needed?

(4) If a field investigation is needed, how many individual exploration sites should be used?

(5) Where should the exploration sites be located?

*b.* What should be done at each individual exploration site?

(1) How many samples and/or field tests should be made in the vertical reach?

(2) What kind of samples and/or field tests should be made?

(3) Would a boring or a test pit be used? If a boring, what kind of boring?

(4) What kind of work platform should be used?

(5) Which laboratory tests should be made on the samples?

(6) Will all samples be laboratory tested? If not, which criteria will be used to describe/classify them?

The development of a site-investigation strategy is typically done by the owner's organization without consultation with the dredging contractors interested in bidding the job. It is unrealistic to expect the contractor to take risks due to incomplete knowledge about the soil characteristics. The sensible objective should be to provide all contractors with a sufficient amount of geotechnical site information so that determining who gets the job depends only on the contractor's capability to manage personnel, equipment, scheduling, and financing. Sufficiency of a site investigation is a matter of the contractor's personal aversion to risk.

## Geotechnical Descriptors for Sediments to be Dredged[1]

Soil properties data can be communicated in two basic ways: (a) as raw numerical soil-identification test data, and (b) as descriptors (Spigolon 1993a). A descriptor is defined as "a word, phrase, or alphanumeric symbol used to identify an item." Numerical test data can be communicated easily using computer database methods. However, this method does not indicate or infer dredgeability directly. Descriptive terms provide word equivalents to the

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[1] This section of Chapter 2 was extracted from Leshchinsky (1994), Richter and Leshchinsky (1994), and Spigolon (1993a).

numbers resulting from soil-identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information.

Descriptors for dredging-related soil properties can be any of the following: (a) descriptive terms (words or phrases), (b) an arrangement of soil properties into classification groups with each group representing an assessment or rating of dredgeability, (c) test results from a specific test device or suite of devices, or (d) some combination of these. Spigolon (1993a) proposed consistent descriptive terms for sediments to be dredged.

Classification indicates a rating or grouping of soil properties into predefined classes according to expected or potential behavior in service. Spigolon (1993a) also proposed a Dredging Classification System that considers all of the dredging processes: (a) excavation, (b) removal and transport, and (c) deposition, as well as all types of dredging mechanisms and equipment. Eight sediment categories are defined.

**Descriptive terms for properties of granular sediments.** Descriptors characterizing the dredgeability of granular soils were developed by Leshchinsky (1994). The descriptors were related to the effective shear strength of granular soils. This strength is a result of both the effective angle of friction and indirectly the coefficient of permeability of the soil. Permeability is used as a measure indicating the ability of the soil to dissipate excessive pore-water pressure developed during dredge cutting. Consequently, permeability affects the shear strength of the soil when rapid shear (i.e., dredge cutting) is applied and thus influences the dredgeability.

A step-by-step procedure to determine the descriptors includes field tests to estimate in situ density and water content, as well as simple laboratory tests to identify the soil and its maximum/minimum densities. As a result, the relative density of the soil, including gravel, sand, and silt, can be estimated. By modifying existing correlations commonly used in foundation engineering, the shear strength and subsequently the descriptors for dredgeability were established. To verify the value of a descriptor for sandy soils, conducting either the Standard Penetration Test (SPT) or Cone Penetration Test (CPT) is recommended. Since these two tests are less direct in defining the descriptor as compared to field measurement of density, the SPT and CPT are considered to provide only supplemental information. The SPT or CPT should only be used if the site consists of sand.

The descriptors of Table 1 were developed based on fundamental concepts in soil mechanics. However, they contain a conversion that was based on judgement (i.e., physical properties of granular soils are converted into a qualitative scale of anticipated difficulty associated with dredge cutting).

It should be pointed out that there is insufficient relevant experience in the dredging discipline to verify the accuracy of the scale chosen for the

**Table 1**
**Descriptors Associated with Dredge Cutting Difficulty for Granular Sediments**

| Angle of Internal Friction | Dredging Difficulty Rating[1] | | | |
|---|---|---|---|---|
| | Permeability | | | |
| | High | Medium | Low | Condition |
| Less than 25° | 1 | 1 | 1-2 | Very loose |
| 25° - 30° | 2 | 2 | 2-3 | Loose |
| 30° - 35° | 3 | 2-3 | 3-4 | Medium |
| 35° - 39° | 4 | 3-4 | 4-5 | Dense |
| Greater than 39° | 5 | 5 | 5 | Very dense |

[1] Descriptors equivalent to dredging rating: 1 = Very easy, 2 = Easy, 3 = Normal, 4 = Difficult, 5 = Very difficult.

descriptors. Therefore, it was recommended by Leshchinsky (1994) that the descriptors be used as a basis for future adjustment and refinement in conjunction with actual dredging operations applying the suggested procedure for determination of the difficulty rating. Special attention should be given to silty soils.

**Degradation of hydraulically transported clay balls.** Materials that are difficult to cut (i.e., boulders or cobbles) are best removed by mechanical means, such as a bucket or clamshell dredge. Extremely loose soils are best removed by pure suction, such as a dustpan or hopper dredge. Cohesive or dense soils are most efficiently cut and moved by a suction cutterhead dredge.

Friction losses and energy expended by transporting material through a pipeline are greatly dependent on the type and rate of dredged material being hydraulically transported. Cohesive soils excavated by a cutterhead typically move into a pipeline as lumps. Similar to noncohesive soils, cohesive ones also are transported through the pipeline by fluid velocity and turbulence. However, unlike sand, if the lumps are not friable, they will be carried as a moving bed in the bottom of the pipe.

Because moving-bed flow is less efficient than suspended-particle flow, the intake of clay materials must be reduced to keep friction and adhesion losses low enough to maintain flow. If the clay is sticky, it may clod and create clay balls (i.e., particles may adhere to each other). As a result, clay materials are typically transported at 4 to 5 percent by volume of in situ material to the total flow in the pipeline. However, some clays begin to slurrify as they are transported, resulting in a decrease in friction loss, thus resulting in a higher percentage of solids.

A method for determining degradation of clays undergoing hydraulic transport was developed by Richter and Leshchinsky (1994). The clays were tested at different compaction levels as related to maximum standard Proctor density. Results of the testing program clearly showed that plasticity and relative compaction have significant effects on rate of degradation.

Degradation effects caused by hydraulic transport were presented by Richter and Leshchinsky (1994) in a convenient form of design charts. This allows predictions regarding degradation to be easily made based on simple and relevant geotechnical properties of the clay to be dredged. An example of these design charts is presented in Figure 1. To use the charts, three properties of the soil to be dredged must be determined, and the hydraulic conditions under which it will be transported must be known. The soil properties needed are the plasticity index (PI) of the soil; the maximum standard Proctor dry density

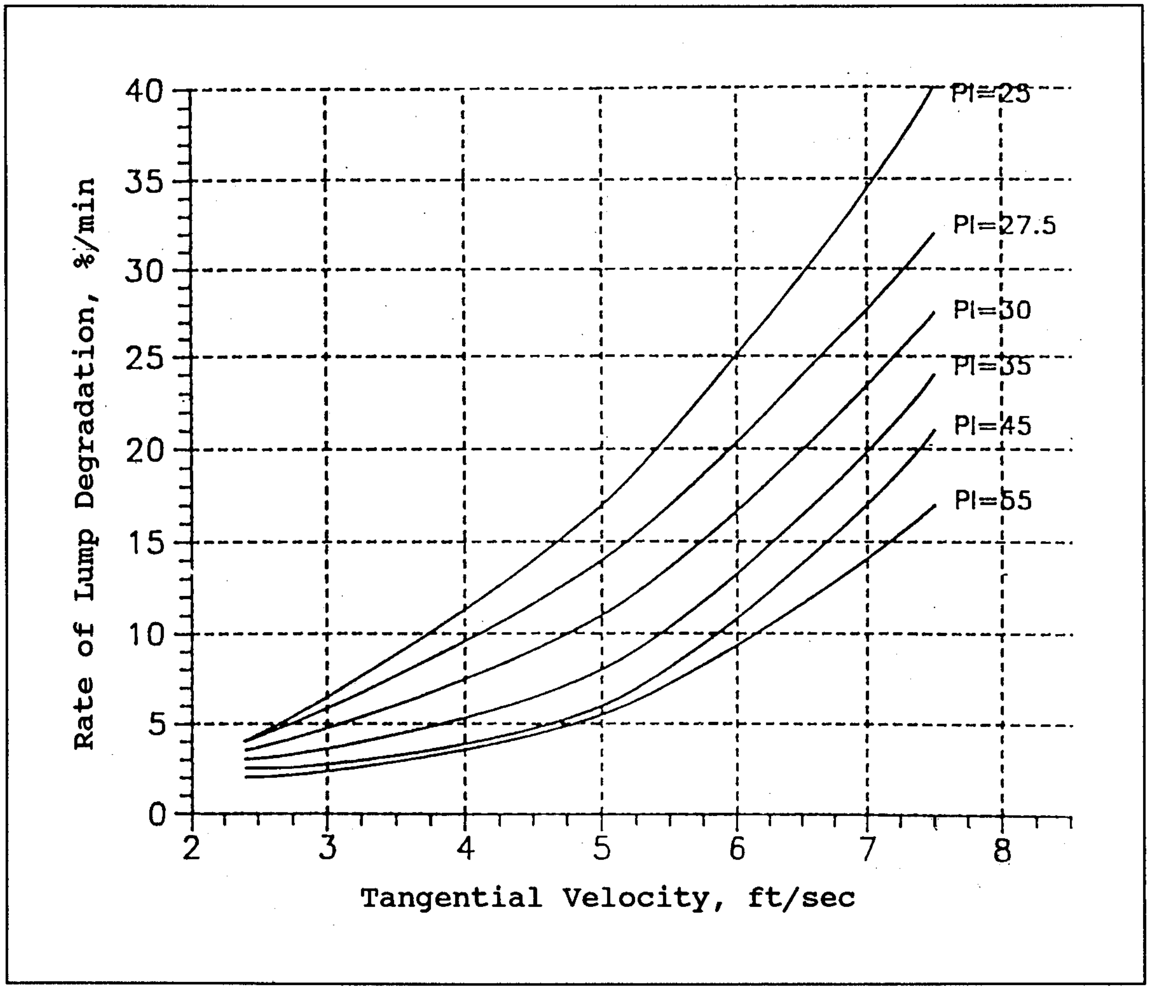


Figure 1. Rate of clay-ball degradation versus relative velocity of transport fluid at relative compaction = 80 percent

of the soil; and the field dry density of the clay, which is a measure of how compact the soil is in its natural state.

Determination of these three properties is a simple and relatively inexpensive process. The hydraulic transport condition needed to make degradation predictions is the velocity of the transport fluid relative to the velocity of the clay lumps. This can be estimated as the difference between the pipeline discharge (i.e., cubic yards of liquid per hour)[1] minus the excavation (production) rate (i.e., cubic yards of excavated clay per hour), divided by the pipe cross-sectional area.

The results presented by Richter and Leshchinsky (1994) have important applications for the dredging industry because they can be used to predict dredged clay behavior. These results provide a rational link between the geotechnical characteristics of clays and the behavior of the material when dredged and transported by cutterhead-dredge pipeline methods.

**Proposed dredging classification system.** Soil classification systems have been established, and are described in the geotechnical engineering textbooks, for various construction-related uses to rate (i.e., indicate suitability of) soils for use in a specific application. Most of them utilize the soil material properties of the disturbed soil as the basis for class grouping without concern for the original in situ mass properties because the systems were developed for application to the use of the soil as a construction material. None of the existing systems indicate dredgeability either directly or indirectly because none of them include in situ strength directly in the classification, nor do they address any other direct needs of the dredging and disposal process.

A classification system for directly indicating or readily inferring the dredgeability of in situ sediments should be based on the following dredgeability properties:

*a.* *Excavation properties*: suctionability, erodability (scourability), cuttability (affected by friability), scoopability, and flowability (underwater slope stability).

*b.* *Removal and transport properties*: pumpability (affected by rheologic properties of slurry), abrasability (abrasiveness in a pipeline), clay balling (affected by stickiness), sedimentation rate in a hopper, and amount of bulking.

*c.* *Disposal properties*: dumpability (affected by friability and stickiness), sedimentation rate in a disposal area, amount of bulking, and compactability.

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1 A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

It has been suggested by Spigolon (1993a) that sediments be placed in the eight groups shown in Table 2, each with different fundamental dredging characteristics. New-work dredging may encounter any of the eight groups. Maintenance dredging will deal mainly with Groups G, F, and M. It is assumed that rock, shale, and cemented soils have been pretreated by blasting, ripping, or any other suitable method. At that point, the material becomes a group of broken angular fragments and can be dredged using one or another of the standard dredging equipment systems.

## Geotechnical Evaluation of the Dredgeability of Sediments Using GEODREDG[1]

There is a continual need for the guidance and training of those persons lacking knowledge and experience in the dredgeability analysis of geotechnical data. It is desirable to retain the expertise of capable persons involved in dredging-related fields and to make their experience available. One highly useful manner for retaining this knowledge and making it available is by means of a computerized knowledge-based expert system (KBES).

### KBES

A KBES is a computer program for the type of problem that requires expertise in a field or discipline for its solution. Conventional programs generally use algorithmic (repetitive) procedures in a predefined sequence for processing data that are primarily numerical. The information (knowledge) and the method of controlling it are integrated; this inhibits mid-run changes in procedure. A KBES uses expertly derived rules for its solutions; the rules can incorporate and process judgement, experience, empirical rules of thumb, intuition, and other expertise as well as proven functional relationships and experimental evidence.

The knowledge base contains a database of facts and "IF - THEN" rule statements that include all of the "IF" questions a typical user is expected to ask and all of the "THEN" solutions. The control system (inference engine) is independent of the knowledge base. An independent explanation facility, consisting of a series of individually accessible texts on relevant topics, is used to explain the rationale for the rules. The separate knowledge base and explanation facility may be edited and modified without changing the other components of the program.

Spigolon and Bakeer (1993) developed a KBES called GEODREDG to provide access to recorded expertise and guidance from experts in the fields of project planning, geotechnical engineering, and dredging estimation.

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1 This section of Chapter 2 was extracted from Spigolon and Bakeer (1993, 1994, and in preparation).

**Table 2**
**Proposed Dredging Sediment Classification System**

| Category | Properties |
| --- | --- |
| **Group R: Rock and Coral** | |
| Geotechnical properties | Rock is massive, solid (nongranular), inorganic mineral matter with an unconfined compressive strength exceeding 1,000 kPa (10 Tsf). Coral consists of living calcareous organisms usually formed into a massive offshore reef. |
| Excavation properties | Hard rock and coral require blasting to break the mass into fragments that can be removed by normal dredging equipment. Softer rock and coral can be easily cut or ripped into small fragments. Cut slopes are stable. |
| Removal and transport properties | Blasted or ripped rock fragments behave like Group B, "Boulders and Cobbles." Hard rock fragments can be abrasive in pipelines. |
| Disposal properties | Blasted or ripped rock fragments behave like Group B, "Boulders and Cobbles." |
| **Group S: Shale and Cemented Soils** | |
| Gotechnical properties | Highly compressed clays (shale) or rocklike soils cemented with iron oxide, lime, silica, calcium, or magnesia; have unconfined compressive strength below that of rock. |
| Excavation properties | Require cutting, ripping, or blasting; usually breaks up into small particles. Cut slopes are stable. |
| Removal and transport properties | Fragments can be removed and transported using either hydraulic or mechanical methods; energy requirement is function of fragment size distribution. Hard angular fragments can be very abrasive in pipeline. |
| Disposal properties | Behavior similar to cobbles or coarse gravel; shale fragments may soften appreciably in air or water. |
| **Group B: Boulders and Cobbles** | |
| Geotechnical properties | Material is dominantly blasted rock fragments or natural boulders and cobbles; deposit typically contains mixture with gravel, sand, and fines; usually insignificant amounts of nonplastic fines. Usually dense and shear strength derives almost entirely from grain-to-grain contact. |
| Excavation properties | Usually excavated by mechanical methods (scooping). Hydraulic methods are usually inefficient. |
| Removal and transport properties | Not easily moved hydraulically. Requires high velocity/high volume hydraulic removal methods or mechanical (bucket) removal and transport methods. |
| Disposal properties | Dumping is easy and coarse particles settle very fast. Very difficult to compact beyond dumped density because of grain-to-grain contact. Low bulking factor. |
| | ***(Sheet 1 of 3)*** |

**Table 2 (Continued)**

| Category | Properties |
|---|---|
| **Group G: Clean Granular Soils** | |
| Geotechnical properties | Material is gravel, sand, or coarse silt with little or no plasticity; will not stand unconfined if dry. Shear strength derives from relative density, grain angularity, and lack of fines. |
| Excavation properties | Excavates easily under hydraulic erosion (scour). Has high friability. Easily cut or scooped. Slopes not stable; tend to flow easily to angle of underwater repose. |
| Removal and transport properties | Easily removed and transported hydraulically. Particles settle very quickly in a hopper. Readily transported in a pipeline slurry; energy required is a function of median grain size. Large particles contribute to pipeline wear. Bulking factors are low. |
| Disposal properties | Dumps easily. Settles quickly in disposal area. Clean granular soils (few or no plastic fines) will densify with vibration. Typically does not respond well to mechanical compaction. |
| **Group F: Friable Mixed-Grain Soils** | |
| Geotechnical properties | Material is mixed-grain soils or low plasticity friable soils, such as small gravel, sand, silt with appreciable clay content. Strength derives from combination of grain-to-grain friction and cohesion due to clay. Friable due to low plasticity of -No. 40 fraction. |
| Excavation properties | Not easily suctioned; too dense or too much clay for easy erosion; typically suitable for cutting or ripping process. Easily scooped. Well suited to cutter suction or bucket-wheel suction process. Underwater slopes do not flow easily; are fairly stable. |
| Removal and transport properties | The soil is friable and will disintegrate during excavation and hydraulic removal; will enter easily into a pipeline slurry. Clay balling is normally not encountered. Sedimentation rate in hopper is typically fast, although disintegrated fines may not settle quickly. |
| Disposal properties | Usually will respond well to mechanical compaction but not to vibration. |
| **Group C: Cohesive Soils** | |
| Geotechnical properties | These are massive fine-grained soils, typically firm to hard clays and silty clays of medium to high plasticity. Not friable. Have sufficient density and clay content to have unconfined compressive strength. Exhibit plasticity, cohesiveness, and dry strength. Little or no grain-to-grain contact; shear strength derives from density, stress history, and amount and type of clay. |
| Excavation properties | Not friable (will not crumble easily); will not suction or erode; may be excavated using cutting or scooping. Underwater slopes are usually stable except for very soft clays. |
| | ***(Sheet 2 of 3)*** |

| Table 2 (Concluded) | |
|---|---|
| **Category** | **Properties** |
| **Group C: Cohesive Soils (Continued)** | |
| Removal and transport properties | Probably form clods during mechanical transport or clay balls in hydraulic pipeline. Low abrasion in pipeline. Will not settle rapidly in hopper; will usually overflow. |
| Disposal properties | Often sticky when water content is high. Take appreciable time to settle in land disposal area. The cohesiveness of the clay prevents the soil from densifying with vibration. Bulking is fairly high. |
| **Group O: Highly Organic Soils** | |
| Geotechnical properties | Peat, humus, and swamp soils are examples. Typically has a spongy consistency, a high water content, and dark brown to black color, although the color alone is not an indicator. Usually has an organic odor in a fresh sample or in wet sample that has been heated. Has a fibrous to amorphous texture and often contains vegetable matter (sticks, leaves, etc.). |
| Excavation properties | May be cut or scooped. Behaves like a soft to firm cohesive soil (Group C), unless fibrous matter interferes with cutting. |
| Removal and transport properties | High gas content may interfere with hydraulic suction. Fibrous matter content may interfere with pipeline transport. Easily moved mechanically. |
| Disposal properties | Organic matter is not usually desirable in a disposal area. Ocean disposal may leave some fibrous matter floating or in suspension. Not easily compacted because of sponginess. |
| **Group M: Fluid Mud** | |
| Geotechnical properties | Mud found at or near the surface of the bottom in harbors and other areas of slow current. Extremely low shear strength; has no unconfined compressive strength; physically behaves like a fluid, i.e., sample will not retain its shape. The solids are mainly silt and clay of low to high plasticity, but may have some very fine sand. Invariably has a very low density and very high water content in situ. |
| Excavation properties | Easily suctioned at or near in-situ density without dilution water. Erodes easily with very little dilution water added. Will not stand on slope. |
| Removal and transport properties | Easily transported in a pipeline; may require addition of dilution water for improved flowability. Fine grains will not settle quickly in a hopper or in a disposal area. |
| Disposal properties | Fine-grained soils do not settle quickly in disposal. |
| | ***(Sheet 3 of 3)*** |

GEODREDG consists of two interrelated KBES programs that have been developed as part of an overall system:

*a. GEOSITE.* Guidance for geotechnical engineers and engineering geologists in the selection of methods and equipment for the sampling and strength testing, field and laboratory, of sediments to obtain the information necessary for evaluation of the dredgeability of the sediments.

*b. DREDGABL.* Guidance in the interpretation of geotechnical properties data for estimating the dredgeability of sediments. Intended to serve the planner or estimator as a personal geotechnical engineering and dredging expert consultant.

## GEOSITE

The objective of GEOSITE is to provide guidance from geotechnical engineering experts for the selection of equipment and methods for a subsurface investigation at an individual exploration site for a dredging project. It is assumed that the number and locations of the exploration sites have previously been established and that there is a general knowledge of the types of sediments to be expected at the site. The GEOSITE program recommends (a) sediment sampling methods, (b) in situ strength testing methods, considering all of the appropriate sampler/testing method combinations, (c) methods for accessing the sampling/testing depth, (d) suitable field work platforms, and (e) material identification tests.

**GEOSITE user's guide**. The user's guide for GEOSITE, prepared by Spigolon and Bakeer (in preparation), contains explicit detailed instructions for application of GEOSITE to a prototype dredging site and operational instructions for navigating through the GEOSITE program, which includes:

*a. Installation instructions*—guidance for placing the Windows version and/or the MS-DOS version of GEOSITE on the user's hard disk.

*b. Operating instructions*—each of the data-selection (input) display and conclusion display screens is discussed and a description of the discussion (help) screen system is presented.

*c. Discussion of background topics*—first, there is a general discussion of KBES and the manner in which they function. Second, the rationale for selecting a relational database-management system as the expert system development shell is presented. Third, the relationship of a KBES to a printed report is examined.

*d. Potential future modifications to the GEOSITE program*—the requested review information is intended primarily for use by programmers and administrators of the development version of GEOSITE.

The GEOSITE User's Guide contains instructions for installing and using GEOSITE. Diskettes for the Microsoft Windows version of GEOSITE are included with each copy of the User's Guide. A limited number of the MS-DOS version are available on request to the Scientific and Engineering Applications Center, Information Technology Laboratory, ATTN: CEWES-IM-DS, USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

**GEOSITE problem-solving strategy.** GEOSITE contains seven knowledge bases: (a) SAMPLING; (b) TESTING; (c) ACCESS; (d) PLATFORM; (e) MATTEST; (f) DENSITY; and (g) ROCKSURF. GEOSITE uses a forward-chaining or data-driven problem-solving strategy. The knowledge representation is rule-based, each rule consisting of an IF-AND<antecedents>...THEN<conclusion> statement. One rule exists for each of the total finite number of options in the antecedents. In the present version of GEOSITE, there are 3,780 rules in the seven knowledge bases. Ideally, each unique set of antecedent options leads to a single conclusion.

**Modifying and upgrading GEOSITE.** KBES programs such as GEOSITE have no completion point; there is always more knowledge that can be added, and there are more conclusions that can be drawn. The program details that are presented by Spigolon and Bakeer (in preparation) are intended for use in the preparation of future upgraded versions of the program.

The program diskettes accompanying the User's Guide are read-only (i.e., any changes entered onto the display screens during a guidance session cannot be stored). The original development version of the program can only be modified by using the Microsoft FoxPro 2.5 Relational Database Management System. The original program diskettes reside with the Manager of the Dredging Operations Technical Support (DOTS) Program, USAE Waterways Experiment Station, ATTN: CEWES-EP-D, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

## DREDGABL

The objective of DREDGABL is to provide guidance from geotechnical engineering and dredging experts for the interpretation of sediment test and observation data in terms of the dredgeability of the sediment. DREDGABL is intended for use by dredging project estimators and planners working for the Corps of Engineers, by dredging contractors, or by dredging consultants. It can also show geotechnical engineers and engineering geologists involved in dredging project site investigations sediment properties that are important to dredgeability evaluation.

DREDGABL provides an expert evaluation of the dredgeability characteristics of specific sediments whose geotechnical properties are described in the dredging contract documents. Advice also is given about the suitability of various types of dredging equipment for use with those sediments, based on

dredgeability characteristics. Expert knowledge is contained in several knowledge databases that are queried during operation of the program.

**DREDGABL user's guide.** The user's guide for DREDGABL, prepared by Spigolon and Bakeer (1994), contains explicit detailed instructions for application of DREDGABL to a prototype dredging site and operational instructions for navigating through the DREDGABL program, in a manner similar to GEOSITE.

The DREDGABL User's Guide contains instructions for installing and using DREDGABL for the geotechnical evaluation of the dredgeability of sediments. The two diskettes for the Microsoft Windows version of DREDGABL are included with each copy of the User's Guide. A limited number of the MS-DOS versions are available on request to the Scientific and Engineering Applications Center, Information Technology Laboratory, ATTN: CEWES-IM-DS, USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

**DREDGABL problem-solving strategy.** DREDGABL, as with GEOSITE, uses a forward-chaining or data-driven problem-solving strategy. The knowledge representation is rule-based, each rule consisting of a number of IF<antecedents>...THEN<conclusion> statements. One rule exists for each of the total finite number of options in the antecedents.

In the present version of DREDGABL, there are 1,035 unique sets of options. Ideally each unique set of antecedent options leads to a single conclusion. DREDGABL reaches 27 different conclusions for each unique set of antecedents, for a total of 27,945 possible conclusions. Inferencing can therefore be done as a standard database search, using the antecedents (IF statements) as search filters to find the conclusion records (THEN statements) that satisfy all of the unique query requirements. By using 27 conclusion fields for each record, the total number of records to be searched is reduced to the 1,035 possible sets of antecedents, greatly increasing the search speed of the system.

**Modifying and upgrading DREDGABL.** As with GEOSITE, the program details that are presented by Spigolon and Bakeer (1994) are intended for use in the preparation of future upgraded versions of the program. Here, again, the program diskettes accompanying the User's Guide are read-only. The original development version of the program can only be modified by using the Microsoft FoxPro 2.5 Relational Database Management system that resides with the Manager of the DOTS Program at WES. The authors request that users evaluate the program's usefulness, screens, and conclusions by considering questions previously asked about GEOSITE. Critical comments and suggestions may be directed to the Manager of the DOTS Program at the address previously provided.

The only database file that can be directly modified by the user in the distribution copies of the DREDGABL program is the LOCLINFO.DBF file.

This file is modified by directly typing onto the memorandum display screen. Instructions for this task are included in the User's Guide. A total of 16 records have been established in this version of DREDGABL, of which the first is used for the instructions. If more than 15 additional records are needed, a provision has been made for adding records. Record numbers and dates should be added to all additional records. There is no practical limit to the number and size of records that can be added except the available space on the user's hard disk.

A local administrator may exercise input control by modifying the LOCLINFO.DBF database file attributes to make them read-only using a file management program such as Norton Commander or Norton Utilities, among others. Alternatively, similar programs may be used to require a password that could be supplied to the appropriate individuals.

# 3 Descriptors for Rock Material to be Dredged[1]

The DRP produced several new products designed to reduce or eliminate adverse impacts of contractor claims about differing and changed conditions arising from incomplete geotechnical information provided to potential dredging contractors. This new technology was developed to enhance the ability of the Corps of Engineers to obtain more precise and comprehensive geological data about proposed dredging projects, with particular reference to new-work dredging. Two of these geotechnical devices are the drilling parameter recorder (DPR) and the point load test (PLT).

Site characterization is of special concern when rock is to be dredged by mechanical (nonblasting) excavation. Differing site condition claims are commonly based on the contention that rock encountered is harder to dredge with available equipment than the contractor had inferred from bidding documents. Such claims necessarily hinge on either the characterization of the rock material or the predicted performance of particular dredging equipment in excavating such material, the two being interrelated. Many of the harbors and river channels where the Corps is involved in planning and contracting rock dredging now have areas of rock bottom. As harbor development continues, more rock will certainly be encountered with each successive deepening. Much of this material will be mechanically dredged. Rock masses that can be dredged using mechanical methods are necessarily weaker and are usually highly variable in strength and rock mass structure.

## Drilling Parameter Recorder

DPR is a generic name for systems used to record the operating characteristics of a drill rig. Devices ranging from paper chart recorders to computerized systems for monitoring drilling production rates and efficiencies are commercially available, but virtually all of them record data relative to elapsed time. For site characterization work, the data record must be in direct correspondence to position in the bore hole. This is the primary reason for selection of

[1] Chapter 3 was extracted from Smith (1994).

an Enpasol recorder and related software for use in dredging-site investigations. For the purpose of this report, "DPR" refers to the WES-modified DPR system using the Enpasol recorder and software by Solentanche. The DPR system described here is the first of its kind to be used in the United States.

### Need for the DPR

In planning and estimating for rock dredging and in resolving differing site-condition disputes, a knowledge of intact rock strength and rock mass structure, as well as the vertical and areal extent of rock, is needed. Typically, less is known of subsurface conditions for rock dredging than for other construction because the rock to be dredged is usually less accessible. Limited bottom borings are often the only indicator of rock conditions.

Rock borings over water involve high costs. For subaqueous drilling, a drilling platform must be provided, and the mobilization and daily costs for this platform can easily exceed all other costs for the drill crew (i.e., costs of drilling equipment and supplies and cost of the drill crew). Also, cored boreholes over water must be cased from above the water surface into the bottom before coring operations can begin. In site explorations for rock dredging, the current practice is to core all boreholes and give results of boring logs at selected locations.

Present assessments of subaqueous rock conditions can be inadequate for the following reasons:

*a.* Frequently, only a small number of borings are available because cored borings taken over water are expensive.

*b.* Core recovery is often poor in the coastal deposits typically excavated by mechanical dredges because the rock is weak and the coring process breaks it.

*c.* Engineering properties other than unconfined compressive strength (UCS), which is commonly the only data given other than a general geologic description, can influence excavatability.

*d.* Although a good geologic description serves to identify the material, it does not directly relate to engineering properties.

### Application of the DPR

DPR theory is similar to other remote sensing technologies, where data are taken by remote sensing at many locations over a site and direct data (based on examination of physical samples from a few locations) are used to interpret the larger body of data. In using the DPR, noncoring drilling operations over water use a tri-cone roller bit to produce a DPR record without the need for

setting casing, which results in a much faster drilling rate than coring operations. In order to save field production time in drilling and logging operations, as well as laboratory testing costs for a given number of holes, most holes can be drilled with a roller bit and the recorded drilling parameters can be correlated with a small number of cored holes, usually paired with roller bit holes and produced without moving the drilling platform. Such a site-specific correlation method is especially important where conditions are highly variable and a large number of boreholes are needed to obtain adequate site coverage.

Some cored holes are necessary at all sites, and certainly all holes may be cored at some sites. In cases where holes are cored and the DPR also is employed, geologic contact elevations can be determined accurately even where core recovery is poor. Even in zones where no core recovery is possible, the DPR provides a continuous record of drilling parameters that are related to in situ material properties. Hard and soft zones can be identified and the location of recovered core pieces within a drill run can usually be identified with certainty. When core recovery is poor, the location of core within the core run is especially critical where a large intact rock-core zone occurs near project depth. If the corresponding zone of continuous rock is above project depth, it must be dredged. Assuming that core is located at the bottom of the core run, which is common logging practice in the absence of other evidence, could easily produce an erroneous record.

## Description of the DPR

The DPR is a data-acquisition system that monitors, measures, and records various physical values called drilling parameters that reflect the operation of the drill rig, thereby producing a record of the characteristics of the formation being drilled. The following eight parameters can be measured, quantified, and recorded on an analog graphical plotter and digitally recorded on tape by a microcomputer integrated into the equipment:

*a.* Drilling fluid pressure.

*b.* Relative torque indicated by pressure to hydraulic motor for the drill string.

*c.* Downthrust on the drill bit.

*d.* Rate of advance (penetration speed).

*e.* Rotation rate.

*f.* Holdback pressure on drill string.

*g.* Reflected vibrations (accelerations).

*h.* Time to drill one digitized increment of depth.

Additionally, accumulated depth of the bit and number of rods in the drill string are recorded, and manual input provides a record of the date, site, boring designation, and the drill rod and bit type.

A software program allows the user to select numerical parameters, plotted parameters, and other pertinent information related to the borehole being drilled. Also, the program organizes the storage of the data on tape (i.e., finds available space, records the data, detects the end of tape, etc.) for later office analysis. The computer portion of the DPR also is equipped with a self-test that detects errors and, where possible, identifies and localizes these problems.

The entire system is interfaced with a drill rig through various sensors that relate physical parameters of the rig and parameters to be recorded. These sensors include a cluster of pressure transducers, a movement transmitter, and an electromagnetic proximity detector. Pressure transducers are connected to the hydraulics of the drill rig and convey drilling fluid pressure, relative torque, downthrust pressure, and holdback pressure of the drill rig to the DPR. A movement transmitter, located at the top of the drilling mast and connected to the rotation head by a cable, provides the feed speed or advance rate. Measurement of the rotation speed is provided by the electromagnetic proximity detector attached to the rotation head of the drill rig. All transducer data are fed back to the DPR via reinforced electrical cables so that no telemetry is used. The entire system has proven highly reliable under rough use in saltwater environments.

### Interpreting DPR results and graphic displays

The DPR software produces graphic displays of any drilling parameter in the following alternative formats:

*a.* A continuous line against depth (so-called "wireline" plot).

*b.* Three different block diagram displays against depth using fixed scale limits, statistical limits, or block names displayed as a function of block amplitude.

*c.* A histogram where data are not presented against depth, but data of a particular parameter in a selected depth interval are statistically evaluated and results displayed as either cumulative or non-cumulative frequency of occurrence.

Figures 2-4 demonstrate several of the various DPR outputs. Data were obtained from a single interval of a boring made at Wilmington Harbor, NC. The DPR can be used for all the sizes of core bits and roller bits for which the drill rig has capability. In this case, a 4- by 5.5-in., 10-ft core barrel was used. The recovered core was badly fragmented and eroded, with the largest

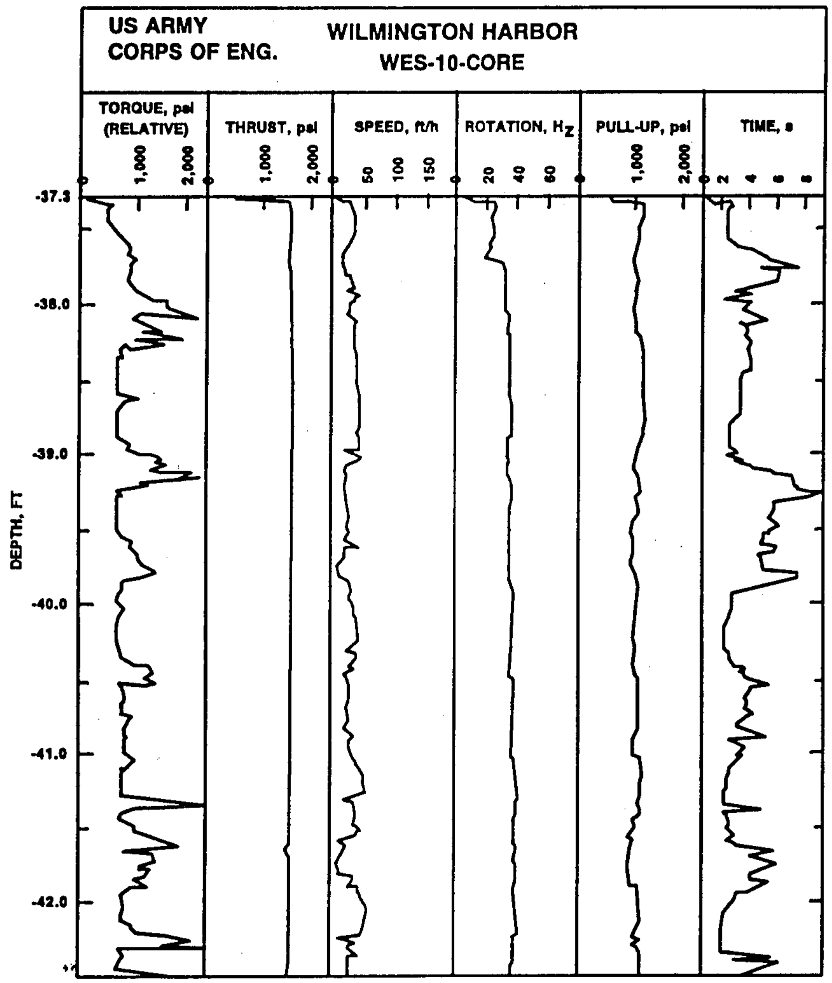


Figure 2. Directly measured drilling parameters

fragment being about 0.8 ft long; approximately 70 percent of the core run was recovered.

Figure 2 shows the graphical plots against depth of six directly measured drilling parameters using the wireline format. Depth is in feet beginning at the top of rod 1. The plot of TORQUE is the hydraulic pressure (psi) in the drill motor, which is a direct indicator of relative torque. Note the responses of the pressure to variations in resistance to drilling. THRUST is the pressure in the forcing hydraulic cylinder, providing a downward force. It is relatively constant because design of the drill rig uses operator control of the PULL-UP or hold-back cylinder to vary the force on the drill string. SPEED is the rate of advance of the bit while ROTATION depicts cyclic frequency of the rotation-rate transducer and can be manipulated to produce revolutions per time, degrees per time, etc. The plotted parameter TIME is the number of seconds

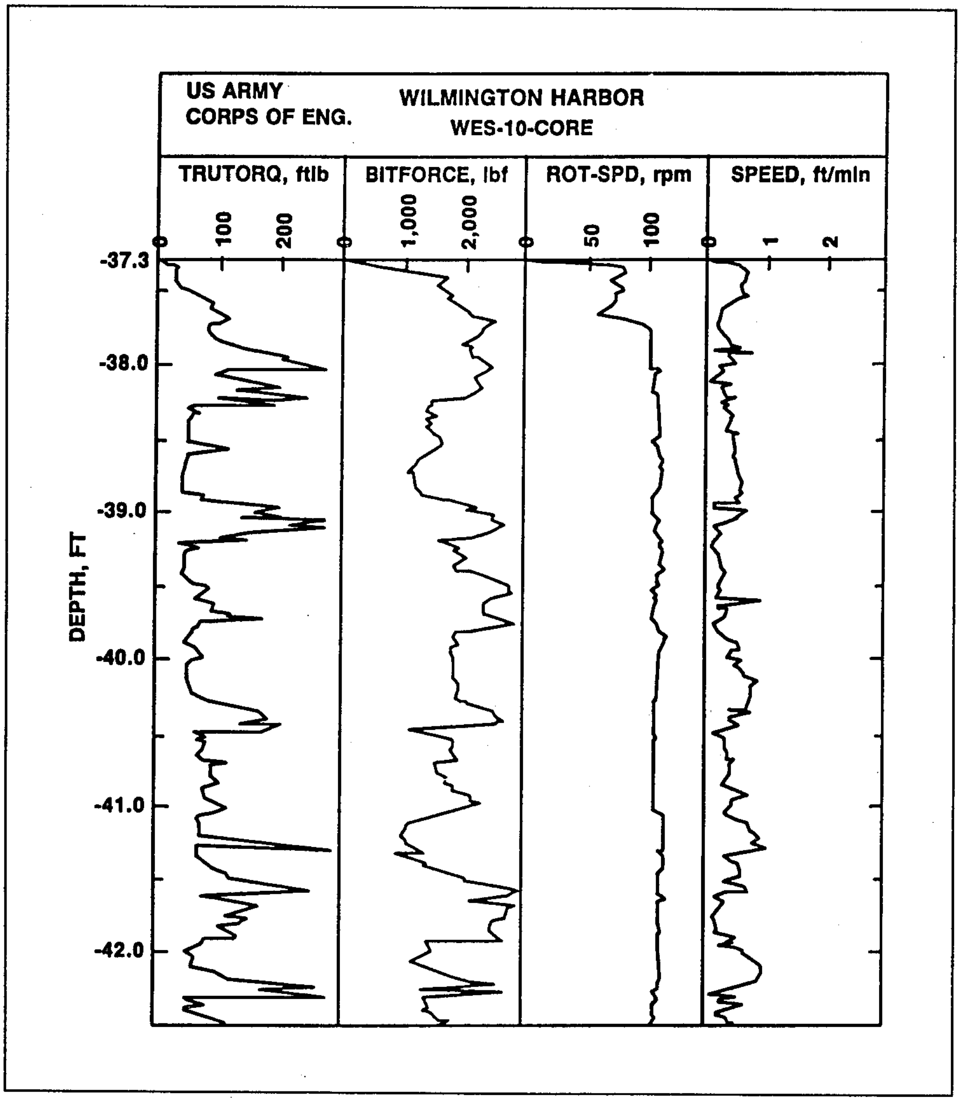


Figure 3. Drill rig mechanical parameters calculated from raw data shown in Figure 2

required for the drill bit to advance one depth increment of 5 mm; it is the inverse of SPEED and can be used as an advance-rate measure in very hard rock.

Figure 3 shows calculated mechanical parameters describing the rig behavior during drilling. The TRUTORQ parameter resulted from applying a correlation equation derived from torque-versus-pressure calibration data. The BITFORCE parameter is the cumulative sum of directed forces and weights bearing on the bit. ROT-SPD is rotational speed of the drill string and bit recomputed to a meaningful unit. SPEED or rate of advance is displayed to a different scale.

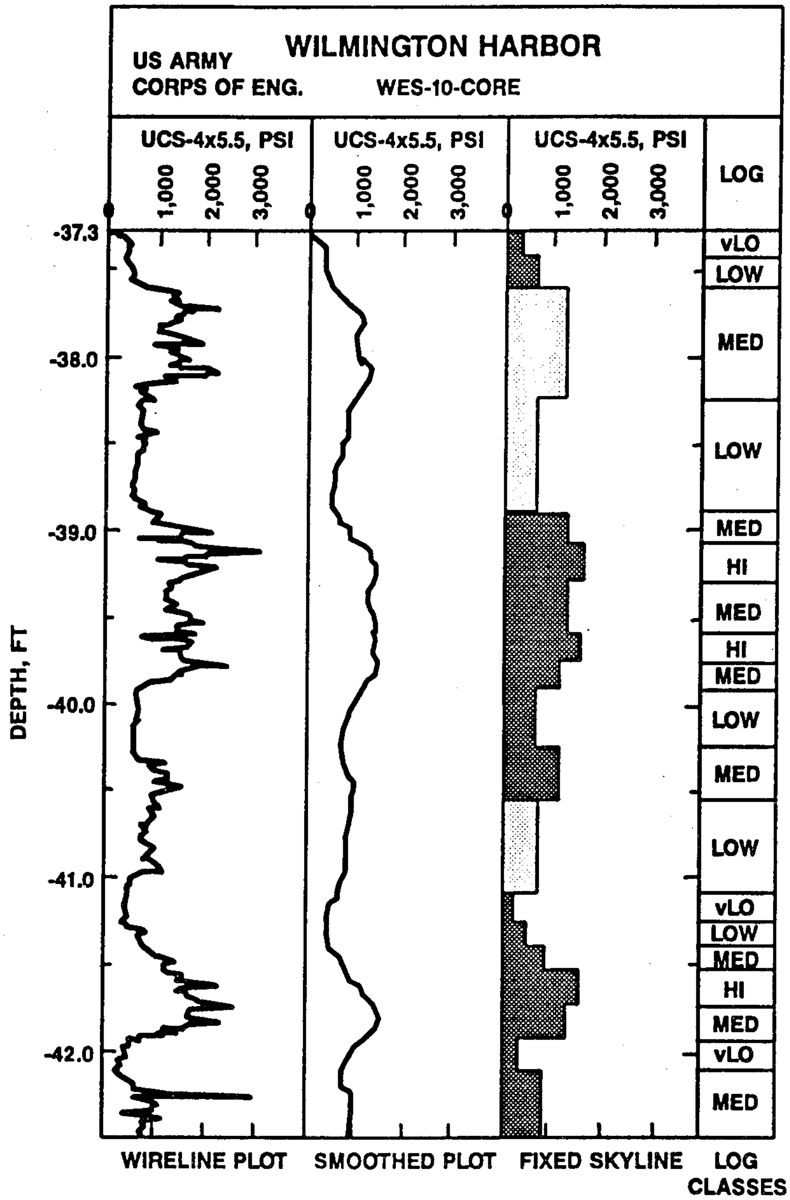


Figure 4. Four graphical forms of combined-parameter estimate of UCS from data shown in Figures 2 and 3

Figure 4 displays the same parameter in four different forms. A combined-parameter estimate of UCS is used here to illustrate these modes of display. The UCS parameter displayed here was computed using data shown in Figure 3. The left-most column is a wireline plot of the computed values while

the second column is a smoothed version of the data. The plot is a running average of 10 data values (i.e., averaged over 0.164 ft).

The third column is a skyline or block representation using fixed proportions of full-scale values of the data. Minimum block height is again based on 10 data values or 0.164 ft of boring. The shading represents the variability of the values within single blocks, darker being more variable. The right-most (narrow) column provides a literal log of the fixed-limit skyline plot in which the nomenclature refers to relative strength.

### DPR correlation with UCS

A subjective review of DPR records and rock-core strengths from field sites indicated a good potential for correlation of drilling parameters with UCS. A laboratory DPR drilling plan was formulated to obtain DPR records in uniform material of various strengths. Blocks of rock from two uniform natural formations, Berea sandstone and Indiana limestone, were placed in the ground at WES to be drilled using the same drill rig and DPR system as was used at the Wilmington field site. To obtain DPR records in a wide range of uniform materials, several different rock simulants were placed in 18-in. auger holes in lifts according to strength class. Rock simulants were produced in target strengths ranging from 300 psi to 10,000 psi using water, portland cement, masonry sand, and bentonite mixes in various proportions.

Results of UCS tests on the rock simulants and the natural rocks are shown in Figure 5, along with results of a linear regression. The resulting correlation coefficient was 0.84. This correlation clearly demonstrates that drilling parameters can be correlated with UCS over a wide strength range involving weak rock.

To infer in situ strengths from drilling parameters, the application approach recommended is to estimate UCS based on a site-specific correlation, since better results were demonstrated over a smaller strength range in the laboratory DPR drilling tests and since the relationship between strength parameters is sometimes material-specific, as was demonstrated by the comparative testing program. A reasonable DPR correlation with UCS was found for both weak and high-strength rock.

## Point Load Test

The PLT was originally proposed as a means of providing for destructive strength testing of hard rock material with a portable apparatus, such that the tests produced could be correlated with UCS. Much of the costly laboratory testing requiring large stationary machines could be avoided in exploration for rock site characterization. The PLT loading geometry produces a failure mode that closely approximates a tensile failure and correlates well with the uniaxial

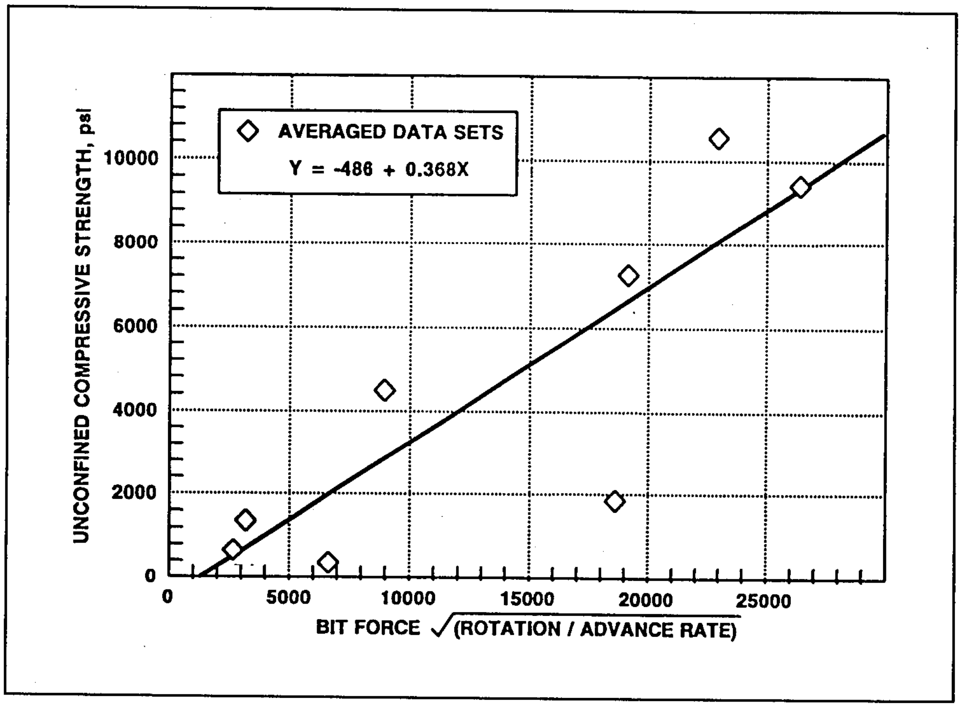


Figure 5. DPR drilling test correlation with UCS

tensile or the Brazilian tensile test strength. Accordingly, correlation of point load strength with UCS could be expected to closely follow the tensile strength to UCS correlation for a given material. For this reason, correlation of point load strength to UCS is material-specific.

## PLT standards

The International Society for Rock Mechanics (ISRM 1985) published a suggested method for determining point load strength. This ISRM standard was incorporated in the *Rock Testing Handbook* (RTH) (U.S. Army Engineer Waterways Experiment Station 1989) as RTH Standard 325-89, replacing the original *Rock Testing Handbook* standard. One change recommended a reference or standard international size of 50 mm where data from size-dependent point load tests on various-sized specimens were to be converted to one size, as is necessary when point load strengths are used for strength-classification purposes. The American Society for Testing and Materials is presently considering a standard test method for determination of the point load strength index of rock.

## Point load tester

Point load tests are performed by loading a sample between two platens having 60-deg conical points with a 5-mm point radius (Figure 6). Thus, a

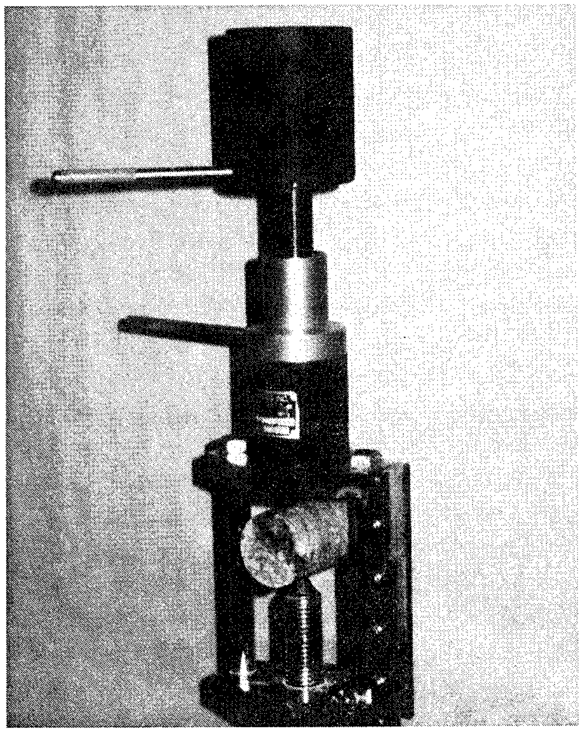

Figure 6. PLT apparatus

sufficient point load can be provided to fail even hard igneous samples using a small portable test apparatus. A typical load capacity is 10,000 to 15,000 lb, which is more than adequate to fail the higher strength rocks when testing NX-size (54-mm) cores. The apparatus consists of an adjustable passive platen and an active platen providing the load through a hydraulic ram; pressure is provided by a second piston manually advanced by a mechanical screw with handle or by a manually operated reciprocating piston with check valve. A hydraulic pressure gauge records pressure at failure, and the gauge reading is multiplied by the area of the piston to give total point load $P$ on the specimen. Different gauges can be used to produce accurate readings for both very high and very low point loads to accommodate a wide range of rock materials.

### Point load index

Results of point load tests are usually expressed in terms of the point load strength index $I_s$ which is determined by dividing the total load $P$ by $(D_e)^2$, where $D_e$ is the equivalent diameter. The index for a given size core is directly related to the material's tensile strength and can be correlated with UCS. Point load tests may be performed on core specimens without standard preparation or on a series of irregular rock fragments. Tests can be carried out using three different sample geometries:

*a.* Tests on cylindrical core may be performed diametrically, in which case no preparation of ends is required. The nearest end point must be at least one radius away from the plane of loading. $D_e$ is taken to be the distance between the loading platens or sample diameter.

*b.* The core may be loaded axially. Core ends must be sawn or split to produce a plane for the platens to bear upon; however, no accurate preparation is required such as grinding the ends. A length/diameter ratio ranging from 0.3 to 1.0 should be used. Very short cores can be tested.

*c.* The irregular lump test can be performed where no core is available. $D_e$ should be as close as possible to the site-size core diameter, especially where diametrical point load tests are also conducted. This test is best performed using a width/length ratio between 0.3 and 1.0, preferably close to 1.0.

In all of these point load tests, ten or more samples should be tested for each material, more if the rock is not uniform.

UCS is the only widely accepted strength criteria for dredging applications today. However, even when making correlations to obtain UCS, the $I_s$ is size-dependent and should be correlated to a standard size when published. The international standard diameter is 50 mm. This index, written $I_{s(50)}$, is often used directly for hard rock classification. The NX-core size (54 mm), which is often used in U.S. practice, is close to this size and correction to NX size is recommended especially when the site exploration used NX-sized core. This strength index would then be designated $I_{s(NX)}$.

## Point load index strength correlation with UCS for dredged rock

Smith (1994) conducted a testing program to demonstrate the applicability of the point load test method for weak saturated dredged rock and to determine any correlation with UCS. Most testing was done on saturated samples; however, some testing of oven-dried sandstones and limestones was done to show wet versus dry strength comparisons.

Dredged material was obtained from core taken at drilling parameter recorder exploration sites at Wilmington Harbor, NC, Kings Bay, GA, and Grays Harbor, WA. Indiana limestone was used to obtain both a wet versus dry strength comparison and an $I_s$ to UCS correlation factor. Berea sandstone was comparatively tested saturated to establish a correlation factor for this very uniform rock of moderate strength. Because the weaker natural rocks are highly variable, a rock simulant was tested to provide an $I_s$ to UCS correlation factor for very low strength material. This material was produced using a portland cement, masonry sand, and bentonite mix to obtain a target strength in the 600-psi range.

The average correlation factor for the three lime rocks was 14.3, which is low compared with an expected value of 24 based on hard rock testing experience. Because weak rock materials are by nature nonuniform in strength, the rock simulant was used to further show that consistent PLT results could be obtained for very weak saturated materials and to obtain a correlation factor for a material in this strength range. The correlation factor was found to be 8.5. The lowest correlation factor found for a natural rock site was 13.2; however, that was for material of much higher strength and of a different type. Test results are presented in Figure 7, which is the variation of UCS with the correlation factor, $K$, where $K = UCS / I_{s(NX)}$.

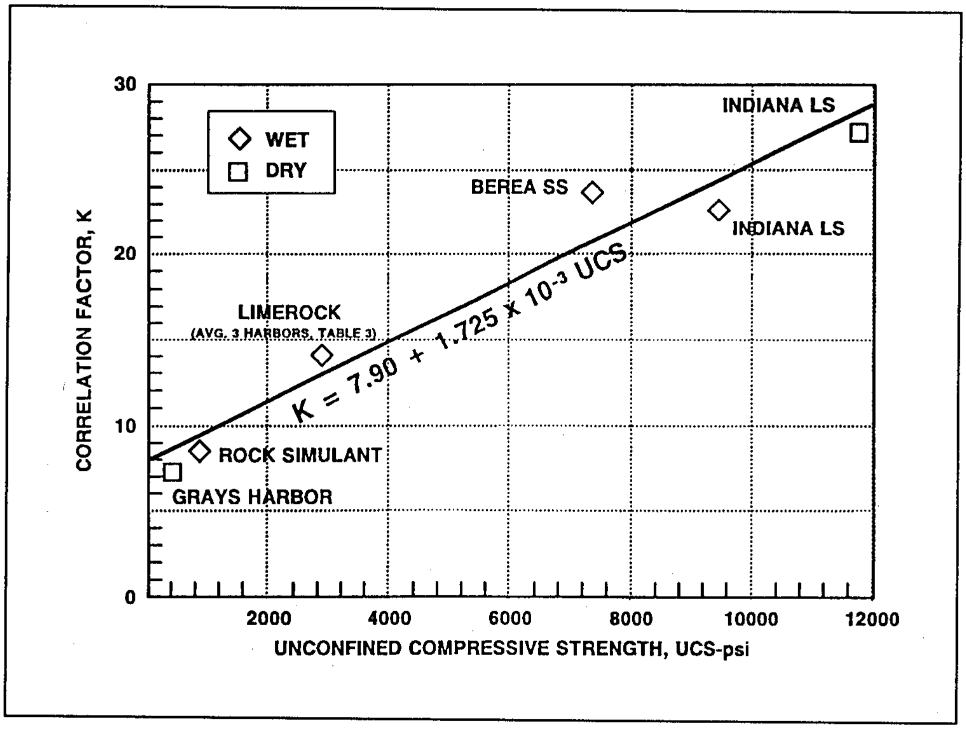


Figure 7. Variation of UCS with correlation factor $K$ where $K = UCS / I_{s(NX)}$

Certainly, site-specific correlation factors for weak saturated materials can easily be one-half or less of published values for hard rock. The linear fit shown is sufficient to demonstrate clearly that site-specific or material-specific correlation factors are lower for weaker rock and that correlation factors in the neighborhood of 10 could be encountered in the very weakest rock.

## PLUCS database system

A database system was developed by Smith (1994) to store, retrieve, and compare rock test data: the point load index and UCS (PLUCS) database system. PLUCS is an open-ended system, which presently contains data from over 400 rock tests from 10 different material sources. About three fourths of these tests were performed on wet samples. In addition to displaying summary data from individual tests such as type test, sample dimensions, and breaking strength, PLUCS will, for a specified material and/or source location, scan the database and compute average strengths, wet/dry strength ratios, and UCS versus point load index correlation factors $K$ (defined as $K = UCS / I_{s(NX)}$). Most point load index tests in this database were performed on NX-sized (54-mm) samples, a size commonly used by the Corps of Engineers. Since the point load index is influenced by sample size and correction to standard size must be made for strength comparison or rock classification purposes, PLUCS software automatically corrects index values to NX size when data are entered so that all index values recorded in and displayed by the database are $I_{s(NX)}$, although actual sample dimensions are stored.

The PLUCS database system is a completely self-contained system that can be executed without additional software and can be executed on any IBM-compatible PC. However, updating of this system does require additional licensed software. An executable version of PLUCS is included in Smith (1994).

# 4 Measurement and Definition of Navigable Depth in Fluff and Fluid Mud[1]

Thick layers of fluid mud occur at some times and at some places, especially in estuaries where fine sediments are often trapped. If the density and viscosity of a particular mud are sufficiently low, it is navigable; however, the margin between navigable and nonnavigable fluid-mud conditions is ill-defined, leading to unsafe navigation and/or inefficient dredging. Fluid mud causes rapid shoaling and special problems for conventional acoustic methods for hydrographic surveying.

A major objective of DRP Technical Area 2, "Material Properties Related to Navigation and Dredging," was the development of a survey tool to determine navigable depth in areas where fluid mud obscures the bottom to conventional acoustic methods such as a fathometer survey. Benefits of a more precise determination of mud bottom depth include improved efficiency in maintenance operations through better definition of what areas actually require dredging or have been sufficiently dredged, and establishing more meaningful dredging priorities and scheduling dredging cycles.

A fluid-mud surveying system was developed that integrates an instrumented towed sled, a conventional dual-frequency acoustic depth sounder, and hydrographic survey positioning-control and logging components. The towed sled has nuclear-transmission density, pressure, cable tension, and multiple tilt sensors. The sled has been adjusted to ride at a certain shear resistance when towed, corresponding to a density slightly higher than that at which the material begins to exhibit continuous interparticle cohesion. The firm-bottom depth is obtained by direct contact with the physical horizon where resistance to motion increases sharply.

1 Chapter 4 was extracted from Alexander, Teeter, and Banks (in preparation) and Teeter (1992a,b and 1994).

## Fluid Mud in Navigation Channels

Many of the fine-grained cohesive fluid muds occurring in navigation channels have densities ranging from as low as 1.05 up to 1.35 gm/cu cm. Concentrations of these muds range from 50-500 gm/l, or from 2 to 13 percent solids by volume. Thick layers of fluid mud occur where fine sediments are frequently resuspended and trapped by hydrodynamic conditions. Fluid muds generally form a lutocline, an area of steep vertical density gradient near the bed. Fluid muds are slow to consolidate and can persist in a fluid-like state for long periods. Wave agitation can maintain muds in a fluid state. Channels where fluid mud is likely to collect have moderately high flows with maximum current speeds of 1-3 ft/sec but with very small net tidal-average current speed. Moderate flow speeds maintain conditions suitable for fluid mud but are unable to completely entrain and disperse the material. Fluid mud can move with the flow, or it can remain stationary and gradually become denser toward the bottom of the channel.

Fluid mud is mobile and navigable if its density and viscosity are sufficiently low. The material property that produces greatest frictional effect is viscosity. However, of the parameters most directly related to navigability, only density can be measured in situ. Flow properties of muds depend on material characteristics such as clay type and content, and therefore fluid muds from different locations can act differently even at the same concentration and density. Fluid muds have density transition points at which viscosity, shear modulus, and yield stress increase sharply. Definitions of navigable or firm-bottom depth for a local site can be based on density (a readily field-measurable physical property) corresponding to a viscosity and strength (not field measurable) near the transition point.

## Surveys in Fluid-Mud Channels

The dilemma for surveying a fluid-mud channel with standard acoustic methods is that high-frequency (200- to 220-kHz) fathometers will return bottom soundings at the upper level of a fluid-mud layer, and lower frequencies (20-40 kHz) will penetrate to firmer layers that can be significantly deeper in terms of a volume calculation. Field tests in fluid-mud channels have documented that firm bottom as defined by a standard lead line can be several feet below the high-frequency depth and several feet above the low-frequency depth. High- and low-frequency fathometer readings at the Gulfport, MS, ship channel have indicated as much as 10 ft between the high- and low-frequency-indicated bottom elevation. Furthermore, fathometer precision diminishes as lower frequencies are selected.

It was desired to develop a towed device (sled) that would furrow into fluid mud and ride automatically at the level being defined as navigable, the vertical location where a significant density transition occurs. The towed sled would make physical contact with the fluid mud and serve as prima facie evidence to

the navigability of the material. This concept assumes the existence of a physical horizon or level where resistance to motion (and navigation) increases sharply and thus where the combination of viscous and normal stresses in the mud support the towed device. That assumption has since been confirmed by laboratory tests and relationships developed between rheologic properties and density for several sites.

## Towed Sled

The behavior of an instrumented sled towed in fluid mud depends on the characteristics of the sled and cable, the manner in which the sled is towed, and the characteristics of the fluid mud. The mechanical system (towed sled and cable) has horizontal and vertical forces distributed along its length that are dependent upon the component submerged weight and drag. The catenary formed by the cable between the survey boat and the towed sled can be calculated for known forces since cable drag forces can be estimated with confidence. However, precise calculation of the drag force on a towed sled in fluid mud is not possible by the present state of the art. The survey sled was designed with body characteristics such that it exerts a moderate vertical force at normal tow angles and is supported by the fluid mud at a level tow attitude. As the sled is towed in fluid mud, the sled tow (bridle) angle is an indicator of relative drag.

The static weight of the towed sled (Figure 8) is about 260 lb in air and 60 lb in water. The frontal area of the sled is about 1 sq ft, the top-view projected area is about 12 sq ft, and the volume of the sled is about 3 cu ft.

The steel-armored tow cable has a diameter of 0.9 in. with a submerged weight of 0.7 lb/ft. The cable termination is 4 in. outside diameter (OD) by 2 ft long and has a submerged weight of about 40 lb. The tension link and tow-angle indicator are located on the termination. The distance between the cable termination and sled bridle is 1.3 ft. The bridle crosspiece is 1.5-in. OD stainless steel, and the cable conductor splice is 4 in. OD.

The tow cable is led over a 36-in.-diam block to an electro-hydraulic winch. The 5-hp winch is equipped with a slip-ring cable-conductor connection and has the capability for computer control. A safety feature on the winch allows the cable to pay out after a 2,500-lb cable load is exceeded.

The following transducers are mounted in or on the sled:

*a.* Nuclear-transmission density gauge uses a 3-millicurie cesium-137 gamma source.

*b.* Hydrostatic pressure gauge measures depth.

*c.* Acoustic doppler unit indicates sled speed.

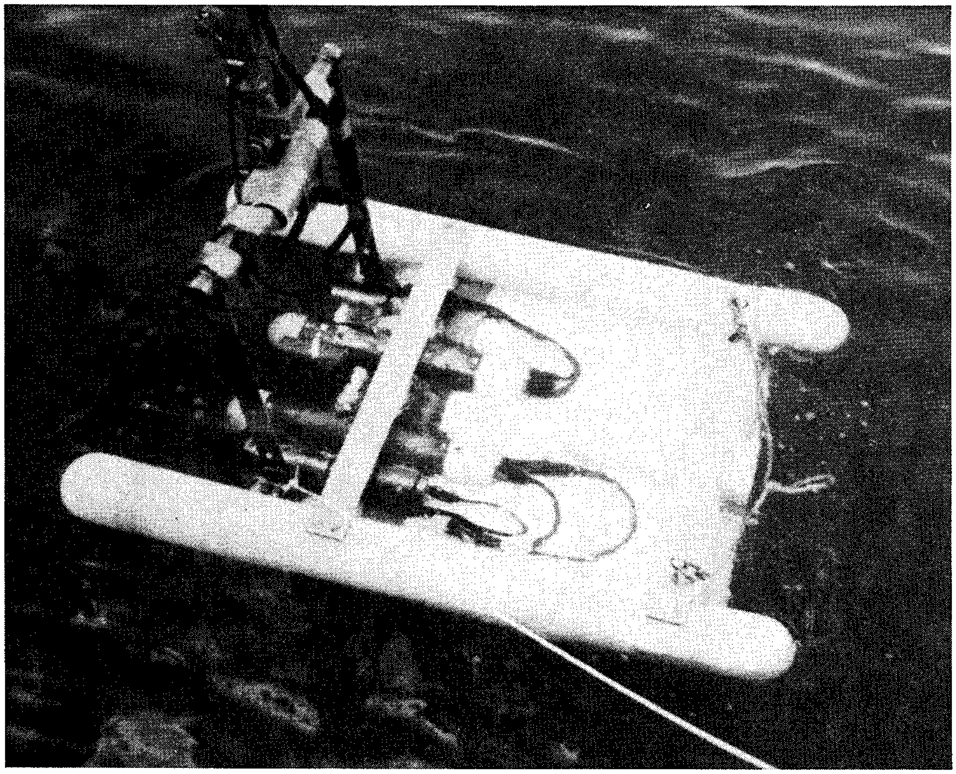

Figure 8. Towed sled for fluid-mud channel surveys

*d.* Tilt sensor mounted on the sled measures sled angle of attack.

*e.* Tilt sensor mounted on the bridle measures cable tow angle.

*f.* Strain gauge between the cable termination and tow bridle monitors cable tension.

*g.* Acoustic transponder beacon indicates location in case of accidental sled separation from the cable.

Onboard the survey boat, fluid mud survey system components include analog-to-digital converters, power supply, density gauge rate meter, data logger, and real-time data display for monitoring sled conditions during surveying. Time plots of all the data from the sled sensors (in engineering units), together with the acoustic depths, are available for evaluation within minutes.

A small boat survey system developed by WES is instrumented for survey control and postprocessing. The survey-system software runs in parallel with the sled data logger on a PC (IBM-compatible) and controls the survey process on a predefined grid. Positioning data are supplied to the system by a Motorola Mini-Ranger Falcon IV. Data for the sled depth, fluid-mud density, and depths measured with high- and low-frequency acoustics are exported from the sled data logger to the survey-system data logger after the survey. During

postprocessing, corrections are made for the tide and for trailback of the sled from the survey boat position. Cross and longitudinal section and plan-view plots can be generated, and dredging or fill volume computations can be made based on survey depths and channel grade.

### Initial field test

Before field testing, the sled was ballasted in a large high-velocity flume at Iowa Institute of Hydraulic Research. The submerged specific gravity of the sled was ballasted to 1.15 gm/cu cm. No further ballast adjustments have been necessary.

Field tests were conducted at the Calcasieu River, Louisiana, entrance channel. The channel center line was surveyed from channel markers 37 to 41 in a thick layer of fluid mud (8- to 13-ft difference between 24- and 200-kHz depth traces). The same line was repeated with variations in survey-boat speed and length of cable played out. Although the recorded depth along this line varied somewhat from one run to another, the recorded density and the overall mean depth along the line repeated well. The sled (without adjustment) was found to track in a narrow range of mud density along a channel while the sled depth varied. Information from the survey and from analysis of samples indicated that the sled followed a physical horizon related to quasi-constant sediment density and viscous characteristics and that the fluid-mud horizon tracked by the sled was not greatly affected by moderate changes in boat speed or cable length.

Initial results supported the design concept (Teeter 1992a). Because the drag of a towed object depends upon the square of the tow speed (roughly), it might be anticipated that boat speed may greatly influence the level of the sled. The sled depth is relatively insensitive to boat speed because the sled is constrained at the level where stresses in the mud support the sled. Limited variations in cable length are taken up by changes in tow bridle angle, which allows for about 2 ft of vertical change in depth between the sled and the end of the tow cable.

Channel debris did not impede towing. During surveys, the sled was lifted to the water surface for inspection after each 2,000- to 6,000-ft longitudinal line. Snagged pieces of seaweed, fishing line, and other debris were found, but nothing changed the towing characteristics of the sled appreciably.

### Channel-grade determinations

In 1991, predredging and postdredging surveys were performed to demonstrate the utility of the fluid-mud survey system in defining navigable depth and channel grade and to define the problems associated with conventional acoustic surveys in fluid-mud channels. A series of longitudinal survey lines were established over a 6,000-ft-long reach of the Calcasieu channel containing

fluid mud. This site was surveyed in June 1991 and again in late November 1991 immediately following completion of maintenance dredging by hopper dredge. Examples of center-line profile data are shown in Figures 9 and 10 for conventional acoustic surveys and towed-sled surveys, respectively.

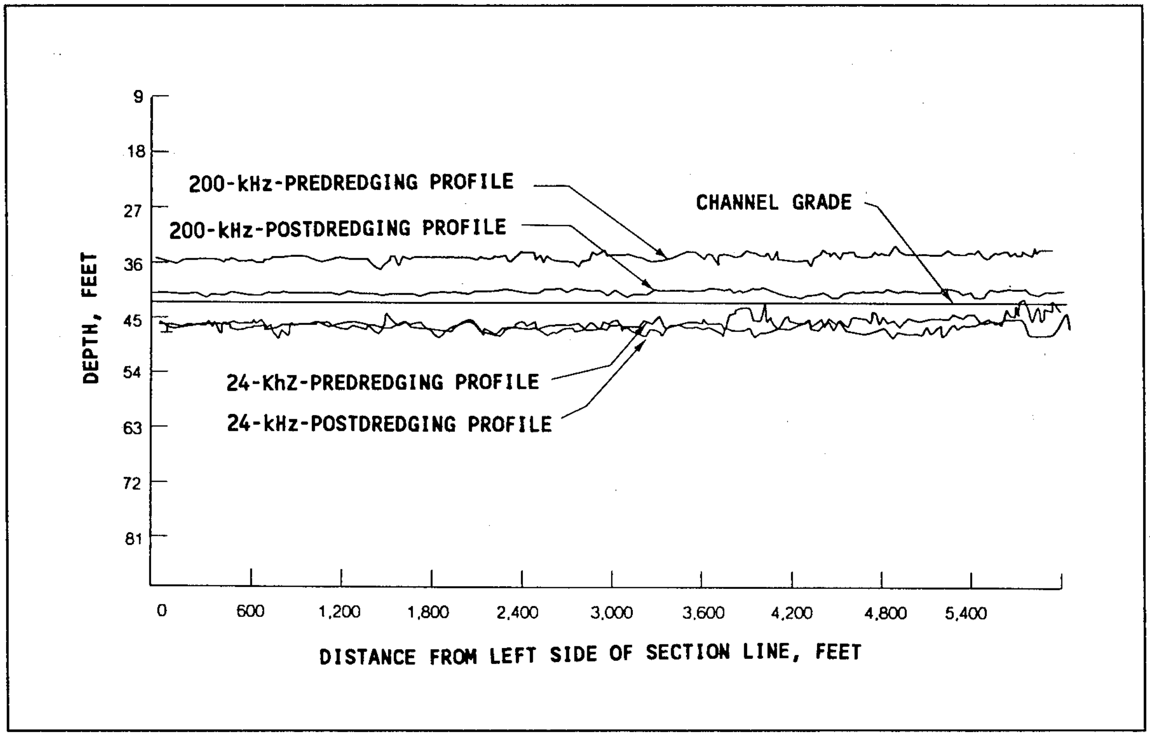


Figure 9. 1991 predredging and postdredging acoustic survey depths, Calcasieu River, Louisiana, entrance channel

As shown in Figure 9, both predredging and postdredging 24-kHz-frequency fathometer depth signals penetrated the fluid mud layers to -45 ft mean low gulf (mlg) datum, well below the authorized project depth of -42 ft mlg. The predredging 200-kHz-frequency survey was about -36 ft mlg, 2 to 4 ft shallower than the towed-sled survey shown in Figure 10. The postdredging 200-kHz surveys also were shallower than the towed-sled surveys. Figure 9 shows that even the postdredging 200-kHz profiles did not indicate that the channel was navigable to the authorized depth of -42 ft mlg.

Acoustic data sets revealed that the 24-Khz frequency may have overestimated navigable depth and thus not indicated necessary maintenance dredging. The 200-Khz acoustics did not always determine whether sufficient material was removed by dredging, nor did they accurately estimate maintenance volumes required to keep fluid-mud channels navigable.

Maintenance operations along the profiled section of the Calcasieu channel include the provision for 1 to 2 ft of advance maintenance (dredging in excess of the authorized depth). Figure 10 shows the towed-sled survey along the

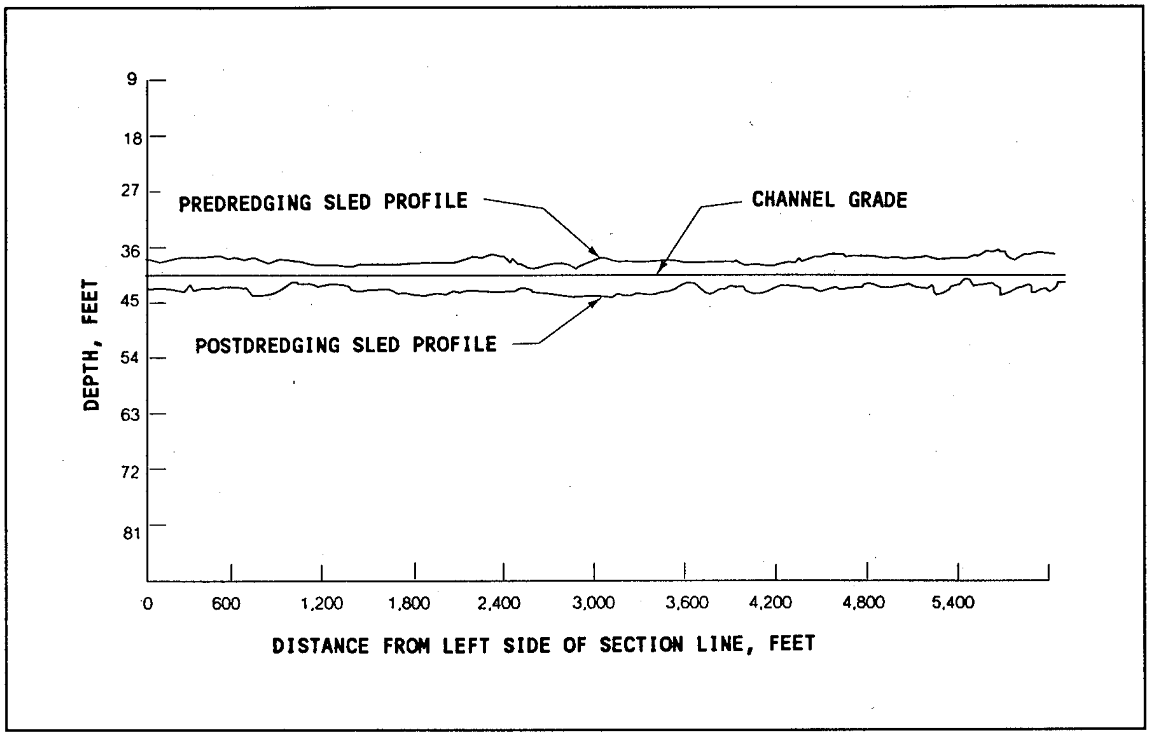


Figure 10. 1991 predredging and postdredging sled depths, Calcasieu River, Louisiana, entrance channel

same profile line shown in Figure 9. According to the sled data, the channel was deepened from -38 ft to -43 ft mlg. This depth information was collected along density levels of 1.19 to 1.21 gm/cu cm. The towed sled was the only survey method used that accurately gauged the amount of material to be dredged or that indicated that the required material was actually removed by dredging. The towed sled will provide vastly improved capabilities to determine channel grade in areas of fluid mud.

## Evaluation

The towed sled developed by WES (Teeter 1992a, 1994) will track on a navigable depth at a constant fluid-mud shear resistance; that is, at about a constant density for a given channel. It can be used as part of a fluid-mud survey system to survey navigation channels at speeds of about 4 knots. Surveys are repeatable and relatively insensitive to operating conditions. Both the towed-sled concept and the hardware developed to demonstrate the concept were proven to be sound. The nuclear density gauge used to monitor performance during field testing probably can be removed from the prototype sled configuration for most applications since knowledge of absolute density in the channel is not essential.

The navigable-depth survey approach will better define channel conditions and allow local Corps offices to more effectively manage and monitor

maintenance dredging operations. Acoustic depth surveys are satisfactory in most areas, but can be augmented by towed-sled data to provide improved information for judging navigation conditions, dredging needs, and dredging effectiveness in those locations where navigation channels are obstructed by fluid mud.

# 5 Rapid Measurements of Properties of Consolidated Sediments[1]

The purpose of this DRP study was to develop a technique to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. A low-noise, high-resolution subbottom imaging system was believed essential. A digital data-acquisition system was combined with specialized processing software to accurately assess bottom and subbottom in-situ conditions.

The objective of the research was to develop the theoretical concept, assemble the equipment, and field test a waterborne seismic acoustic impedance (AI) technique for subbottom imaging. This required development of an electronic package to send and analyze acoustic signals to provide geophysical information such as density, shear strength, and grain size from the acoustic reflectivity strength of the signals. McGee, Ballard, and Caulfield (1995) described the equipment, technical development of the AI concept, data processing and interpretation, data visualization, survey planning, and limitations of the AI technique. The AI technique assesses engineering properties of shallow marine sediments and provides virtually continuous coverage for delineation of both horizontal and vertical extent of those sediments. Several AI surveys have been successfully conducted. The system is available for use in a wide range of problem applications.

## Technology Development

The AI method of seismic shallow-water subbottom investigation for dredging purposes (Figure 11) is an extension of techniques developed by Caulfield and Yim (1983) and Caulfield, Caulfield, and Yim (1985). The AI

[1] Chapter 5 was extracted from Ballard et al. (1993) and McGee, Ballard, and Caulfield (1995).

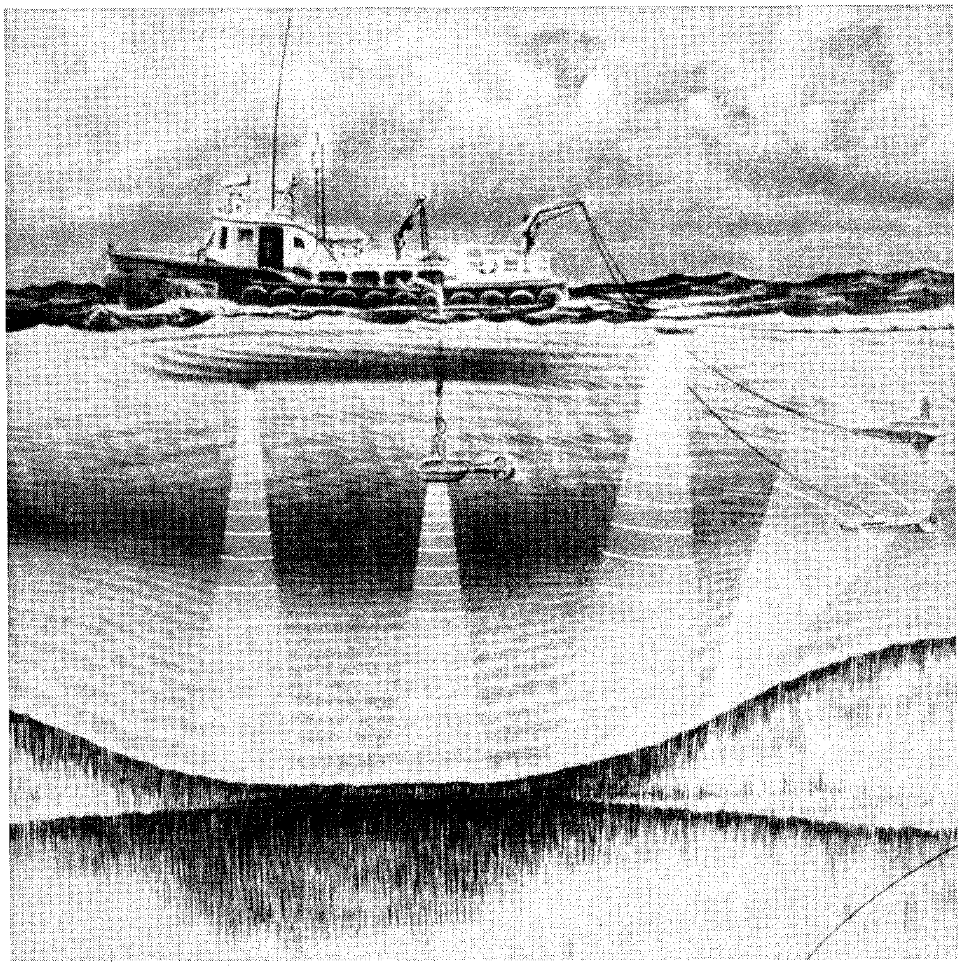

Figure 11. Seismic acoustic impedance subbottom profiling for dredging

model is an empirical technique that compensates for absorption in each layer as a function of the center frequency of a band-limited seismic trace, corrects for spherical spreading, and utilizes classical multilayer reflective mathematics to compute reflection coefficients at sediment horizons. Reflection coefficients are converted to impedances and classified according to established relationships between acoustic impedance and geotechnical properties of marine sediments, thereby classifying the lithostratigraphy.

### Acoustic reflection

The principles governing acoustic reflection are well-known. If a seismic wave propagating through a medium arrives at the boundary of another medium, part of the energy of the wave will be reflected, a portion absorbed within the upper medium, and part transmitted into the next layer. It is possible to represent the relationship among incident, reflected, and transmitted waves in terms of their velocities and angle of propagation relative to the normal. For a perfectly elastic medium, the AI is the product of the density of

the material and the velocity of compressional (P-wave) propagation across the boundary of a horizontally oriented system. The multilayered system presents many variables not evident in the simple case of wave propagation across a single boundary. The effects of upward-traveling waves and absorption must be considered. To accurately determine the reflection coefficient, and thus impedance, at a given interface, the energy loss resulting from absorption must be accounted for.

### Absorption losses

One of the primary energy losses encountered during acoustic wave propagation through differing media is loss due to absorption. Acoustic reflections are generated from impedance mismatches within the sediment body. The amount of returned energy depends on the length of the sound path and the attenuation of sound along the path. Attenuation along the sound path results from a number of mechanisms, including:

*a.* *Spherical spreading or transmission loss*—a geometrical effect representing the regular weakening of a sound signal as it spreads outward from the source. Spreading loss varies with range according to the logarithm of the range.

*b.* *Transmission through reflectors*—multiple reflections, reflection and refraction, and conversion of compressional to shear waves.

*c.* *Reflector roughness and curvature*—focusing and defocusing effects of concave and convex reflectors.

*d.* *Scattering due to inhomogeneities*—variations within the sediment body.

*e.* *Intrinsic absorption*—process of conversion of acoustic energy into heat, it represents a true loss of acoustic energy to the medium.

### AI model for dredging applications

The total of all acoustic losses is called the effective attenuation; because of the randomness of items *c.* and *d.* above, it is nearly impossible to completely account for such attenuation in the real world of acoustic profiling. However, the major sources of attenuation (i.e., spreading, reflection, and absorption) have been researched extensively, providing reasonable approximations of the actual losses occurring.

For the case of absorption in marine sediments, there has been considerable debate concerning the most appropriate attenuation model. Hamilton (1972a,b) presents convincing experimental evidence as to absorption's relationship to the first power of frequency. Because of the extensive experimental data,

Hamilton's linear relationship was chosen as the model for the AI method developed by McGee, Ballard, and Caulfield (1995). A modification of this model as described by Caulfield and Yim (1983) and Caulfield, Caulfield, and Yim (1985) was utilized in the AI method to estimate the engineering properties of marine sediments. The model utilized in the AI method is not perfect in terms of applicability to all possible marine environments. However, it is designed to provide a reasonable estimate towards the prediction of actual sediment properties and, upon critical examination of actual in situ conditions, can be refined to precisely model a particular sediment environment.

## Relationship of AI to Geotechnical Properties

Because AI basically represents the influence of a medium's characteristics on reflected and transmitted waves, many geotechnical properties (such as porosity, density, mean grain size, bulk modulus, etc.) exhibit excellent correlation with impedance. During the last two decades, the ability to predict geotechnical properties from normal reflectivity through impedance calculations has become very well established. However, seismic signatures and, therefore, acoustic impedances are not considered unique. Several combinations of geologic conditions could conceivably yield similar signal characteristics. Hence, a critical stage in the process is development of geoacoustic relationships that are used to model a specific geologic environment. General relationships for AI versus soil type are presented by Caulfield and Yim (1983) and are shown in Table 3. These relationships are based on worldwide averages of impedance versus sediment properties and do not necessarily constitute the precise characterization of all geologic situations.

**Table 3**
**Soil Classification Versus Acoustic Impedance**

| Description | Acoustic Impedance x ($10^2$ g)/($cm^2$ s) |
|---|---|
| Water | 1450 - 1550 |
| Silty clay | 2016 - 2460 |
| Clayey silt | 2460 - 2864 |
| Silty sand | 2864 - 3052 |
| Very fine sand | 3052 - 3219 |
| Fine sand | 3219 - 3281 |
| Medium sand | 3281 - 3492 |
| Coarse sand | 3492 - 3647 |
| Gravelly sand | 3647 - 3880 |
| Sandy gravel | 3880 - 3927 |

Utilizing proper calibration procedures with data of high signal-to-noise ratio, seismic reflection data can be processed to accurately estimate the density and soil type of bottom and subbottom sediments. Site-specific calibrations are performed on every job by correlating acoustic impedance calculated from seismic reflection data at a core location with in situ information (density, mean grain size, etc.) at that location. Experience to date has shown that calibrations made at a few locations within a geologic region produce the shallow seismic parameters necessary to adequately calibrate and describe the entire region.

In specific geologic regions such as the Mississippi Sound, Savannah Ship Channel, or San Francisco Bay, differing sediment units usually have a characteristic and relatively narrow range of impedance values. There, using calibration procedures that incorporate local core and laboratory data, seismic reflection data are processed at known sample locations to yield acoustic impedance values of the known reflection horizons.

## Density predictions

Estimates of in situ density are derived from computed impedance values and correlated with ground-truth information. Plots of acoustic impedance versus core density for consolidated materials in Mobile, AL, and Gulfport, MS, ship channels, presented in Figure 12, document agreement to be within 1 percent of the predicted impedance function. By incorporating the virtually continuous coverage of subbottom materials with digital terrain-modeling techniques, rapid and accurate computations can be made of volume and material type to be removed by dredging. Computer-generated sediment densities within the project area can be displayed in a color-coded three-dimensional (3-D) view as represented in the black-and-white illustration shown in Figure 13.

## Volumetric calculations

Before computer-assisted volume estimates can be calculated, a continuous 3-D computer model of the subbottom data must be generated for each survey line. In addition, a 3-D perspective model consisting of a composite of data from all individual survey lines may be created for use in modeling proposed channel cuts, evaluating slope stability, etc. The project planner may wish to view an area of interest from various angles or create different displays by stripping or slicing at any desired coordinate.

The volume of any material to be removed can be easily calculated. Calculating the volume of material present within a selected area of the perspective model is accomplished by calculating the volume of material present within the corresponding area of each profile-line model. Before calculating volumes, the area of interest must be sliced out of the computer model and the material density range to be displayed must be selected.

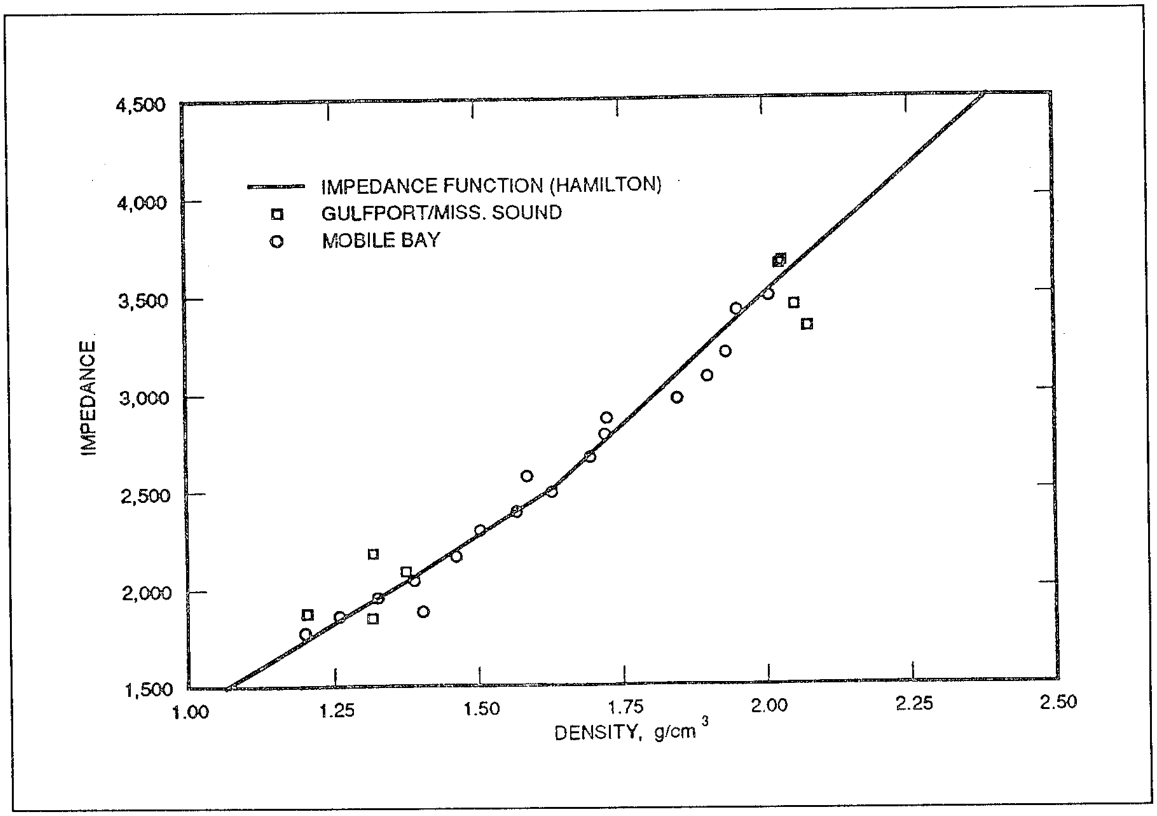


Figure 12. Computed AI versus in situ density compared to predicted impedance function

## AI Equipment

### Hardware

A wide range of shallow seismic data-acquisition systems, beginning with analog and transitioning to digital, were utilized during development of the AI method. A variety of off-the-shelf commercially available equipment can be adapted to AI technology. A block diagram showing equipment used in the WES integrated geophysical system is shown in Figure 14. This system is currently used to perform AI surveys and other types of marine geophysical investigations. Specific systems utilized for the AI applications include:

*a.* *Pinger system (3.5- and 7.0-kHz).* This system allows transmission of variable-length pulses (0.2 - 3.0 msec) of 3.5- and 7.0-kHz frequencies. Power levels can be varied from 1 to 10 kW. However, depth of penetration can be limited in areas of highly competent (dense) sediments. To improve signal/noise, a separate receiving array is deployed independent of the transmitter. By decoupling the receiving array from the transmitter and physically separating the transducers, all of the near-field transmitter ringing is eliminated from the bottom reflection, regardless of water depth.

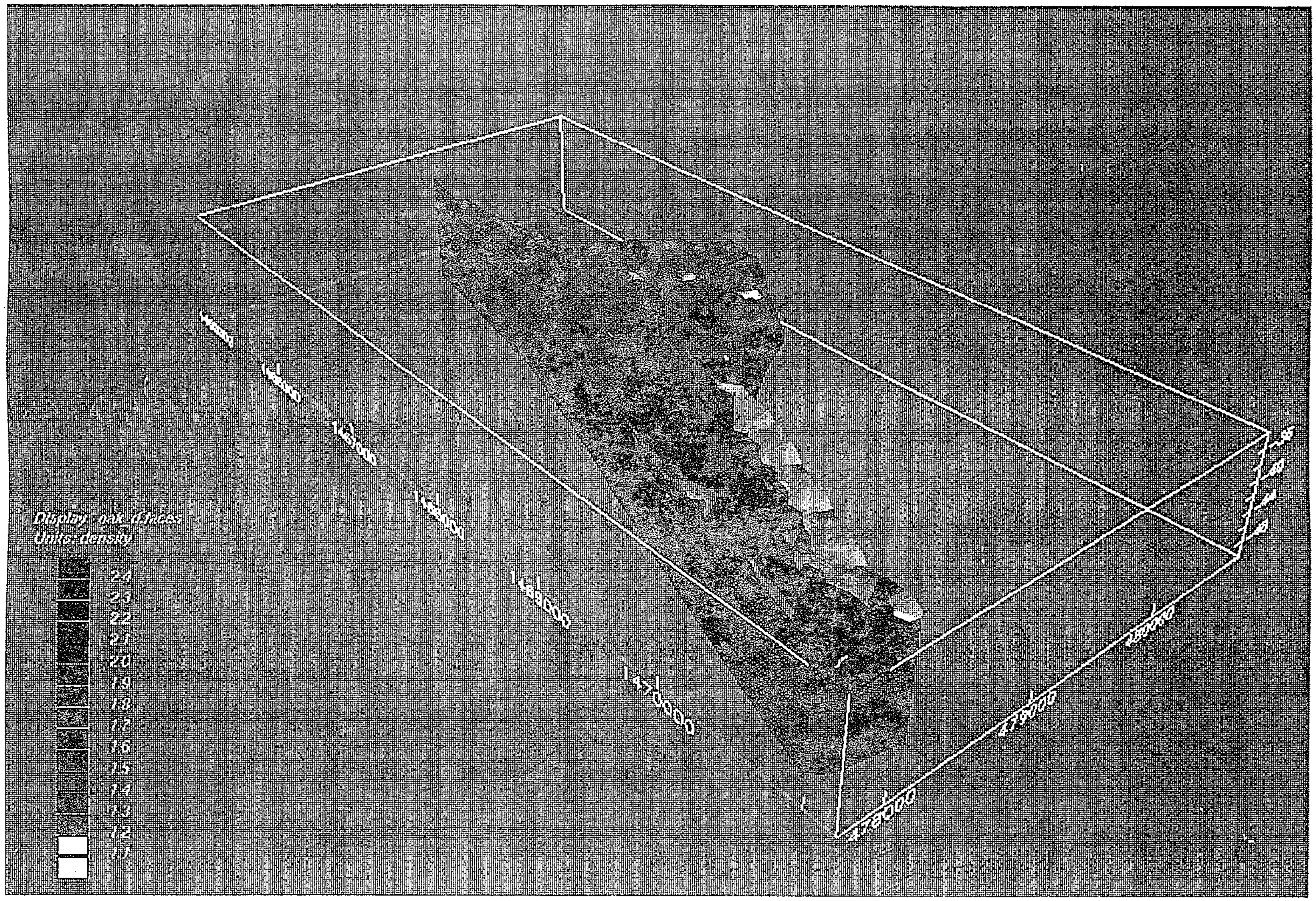


Figure 13. Black-and-white representation of a color-coded 3-D visualization of a portion of Oakland Harbor, California, channel-deepening project

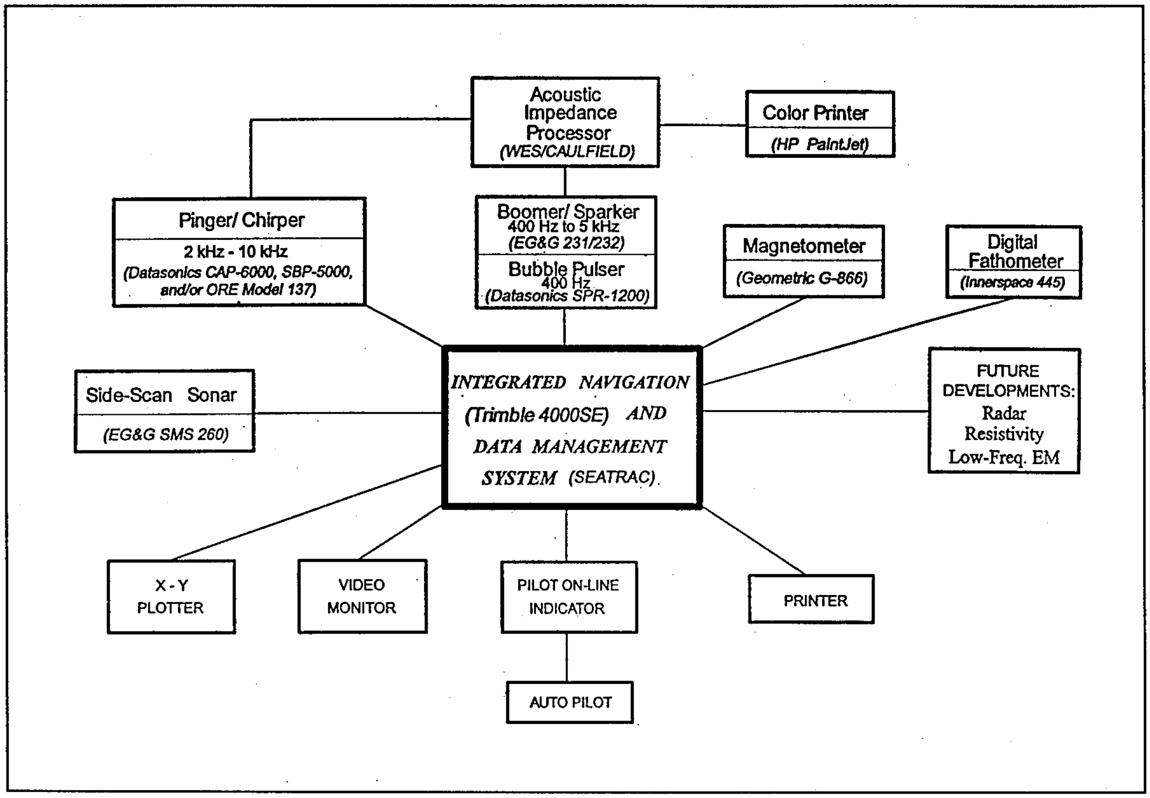


Figure 14. WES integrated geophysical system for conducting AI subbottom surveys

b. *Boomer system.* This system is a high-energy, medium-bandwidth unit providing up to 1,000 J of energy in the 400- to 5,000-Hz frequency band. The system is designed to provide reasonable vertical resolution combined with greater penetration depths in more competent sediments. Because of the high power involved and because the coherent noise radiates to the receiver as well as to the bottom, a separate towed receiving array is used. This array is normally towed at right angles to or directly aft of the source. The exact tow point is determined by the water depth and by minimizing the coherent noise to the receiver. The source-to-receiver separation can be fine-tuned by an experienced data observer to produce the best record quality obtainable at a specific site.

c. *Chirp system.* Commercially available chirp systems (analogous to land-surface vibrators used in the petroleum industry) are designed to improve the signal/noise and vertical resolution by application of correlation processing (matched filtering) to a wide-band swept-frequency long-pulse signal. Standard chirp systems normally operate from 1 to 10 kHz with pulse length of 3 to 20 msec. (Only the chirper transducer was used in development of the AI method.) Since the mid-frequency energy range of most chirp systems is around 4 kHz, the depth of penetration achieved is about the same as pinger systems. As with the pinger system, the receiving array is deployed independently of the transmitting array. This procedure greatly improves the

signal/noise by eliminating the coherent noise resulting from transmitter ringing. The complete chirp data-acquisition system developed by WES allows for unprecedented flexibility in generating wave forms. In many cases, the need arises for tailoring the seismic source to produce maximum energy within a predetermined frequency/wavelength band for resolution of a site-specific target. Chirper transducer-control software was developed by WES to allow the design of virtually any waveform type (within the design limits of transducer response) as a function of frequency, amplitude, and pulse length. This wave form is delivered directly to the power amplifier of the chirp transceiver through a digital-to-analog signal converter, linear amplifier, and analog filter.

*d.* *Bubble-pulse system.* The bubble pulser generates a low- to mid-range frequency wavelet, with a frequency content between 400 and 2,000 Hz, with most of the energy concentrated between 600 and 900 Hz. Because of the source's low-frequency content, penetration depth in competent materials such as sands is significantly greater than with the 3.5-kHz system. Because the bubble pulser exhibits bandwidth rather than single-frequency energy, the same correlation techniques to improve resolution in chirp technology can be applied, improving the signal/noise and resolution by a factor of two.

Based upon results of numerous surveys, it is recommended that multiple systems, preferably with different frequencies and energy levels, be utilized for all AI surveys. For most Corps dredging applications, high-resolution delineation of surface sediment layers is important, requiring higher frequency devices and/or chirp technology. To accurately assess the absorption characteristics of subbottom sediments, multiple frequencies encompassing the greatest bandwidth are required.

## Software

Reflected acoustic signals detected by the receiving array are first amplified and filtered as needed to ensure maximum signal/noise. The amplifiers must be linear and must exhibit no direct current bias. The AI method requires precise knowledge of the total energy due to signal amplification. Real-time filtering is provided at the front end of the amplifiers to reduce undesirable noise as much as possible prior to digital sampling of data. After this preprocessing, data are recorded digitally using a specially designed Digital Field Shallow Seismic Acquisition System (DFAS).

The DFAS is designed to provide an economical means of recording shallow marine seismic data on commonly available computing systems. The DFAS is an IBM-compatible hardware/software package that operates under DOS 3.3 or greater. The system has a minimum dynamic range of 72 db and provides real-time visual color display, disk-writing procedures, and a data-processing and playback system.

Real-time data acquisition is based on the data input being wide band and having sufficient signal/noise levels to meet standard communications quality-control conditions. Acquisition quality control is provided to verify that the amplifier gains are set for optimum signal/noise, appropriate sample rates and trace lengths are chosen, and appropriate timing offsets are employed to maximize the reflection window. The system is designed to handle most standard shallow subbottom geophysical tools, such as the 3.5-kHz pingers, boomers, etc. The analog/digital converter has a 12-bit, 20-msec sampling rate with precision sample and hold amplifiers on the front end. The actual operational sample rate is dependent on the host computer and is software controlled.

The system has been designed to operate with any user-supplied navigation system that has RS-232 output. Navigation information is read directly into data-file headers for direct correlation with subbottom data.

Limited postprocessing options are provided. These include horizontal-spatial stacking, noise reduction, and linear-gain manipulation. Also, data may be played back utilizing the spherical-spreading correction to compensate for transmission loss.

Chirp data are recorded using Real-Time Correlation Acquisition (RTC10) System shallow seismic software. This system provides real-time matched filter correlation processing of echo time series with a true replica of the outgoing source wavelet.

## Boundary Conditions and Limitations

The AI method described by McGee, Ballard, and Caulfield (1995) represents an engineering solution to a problem of remotely assessing the physical characteristics of marine sediments. The system is not a device capable of assessing every conceivable geoacoustic situation occurring in the real world; therefore, it is important that boundary conditions and limitations of the technique be understood.

### Boundary conditions

A number of important assumptions and limiting conditions have been made in developing this AI method and are summarized as follows:

a. *Sound wave front propagated as a plane wave acting at normal incidence to a horizontally layered system.* Virtually all commercially available underwater profiling systems produce spherical wave fronts with either highly directional or omnidirectional beam patterns. Certain beam pattern and bottom type combinations can significantly influence the quality of a reflected signal. For Corps projects such as ship channels, disposal mounds, or high-energy sediment zones, the bottom topography may not be horizontal. A rapidly changing bottom topography

will alter the integrity of returned echoes by either redirecting the echo away from the receiver or focusing too much energy towards the receiver. Also, side echoes reflected off vertical objects or barriers can produce anomalous subsurface reflectors.

b. *Increasing impedance environment.* The initial approach assumed a geologic environment of increasing impedance layers (i.e., sediments become more competent with depth). Whereas this assumption holds true for many geologic situations, there exist numerous situations where soft sediments are overlaid by more competent materials. Techniques are provided to externally compensate for this condition.

c. *Natural marine sediments.* The initial impedance function used for this technique is based on empirical data collected in naturally occurring marine sediments from primarily deeper offshore environments. Therefore, this algorithm, without confirmatory core information, may produce anomalous estimates in the dynamic nearshore, harbor, and riverine environments. This is the primary reason for the regional calibration approach.

Whereas these assumptions provide a practical engineering approach to the solution of a very large number of problems, they may also limit the technique's ability to correctly assess a specific situation. There is no one single sound source or analysis methodology that addresses all engineering and geological requirements.

## Limitations

As with any remote sensing technique, limitations that exist in the system must be understood to appropriately use the method. The most common fault encountered in geophysical studies is improper application of a given technique for a given study objective. The following limitations exist for the AI technique:

a. *Signal/noise ratio.* The ability to accurately assess any environment is strictly a function of the quality of data obtained. Low signal/noise data will produce poor quality results or possibly no results at all. The AI method limits its processing to data with a signal/noise ratio greater than 5 db. It is wise to be suspicious of impedance predictions in areas of poor signal/noise. Fortunately, most noise problems can be corrected through effective vessel mobilization and acoustic calibrations.

b. *Layer identification.* Unique sediment units can be identified only when an impedance change exists. Gradual change in soil type may not result in an impedance differential large enough to produce a reflection.

*c.* *Resolution.* Vertical resolution and ultimate depth of penetration are dependent on the frequency of the sound wave. Higher operating frequencies permit greater resolution of marine sediments but shallower depth of energy penetration, depending on the characteristics of subbottom materials. Also, in high-attenuation sediments, higher frequencies are attenuated at a higher rate than low frequencies, resulting in degradation of resolution and errors in absorption estimates for very deep layers. A number of field techniques and processing methodologies available now concurrently improve resolution and depth of penetration. However, it cannot be overemphasized that these techniques require data with high signal/noise ratios.

*d.* *Multiple reflections.* Multiples are one of the primary causes of data-quality degradation in shallow marine seismic measurements. Unlike noise, which can be distinguished from data by its lack of lateral continuity, multiples can easily be mistaken for real data, create false structures, and change reflectivity estimates. Presently, no multiple-suppression techniques have been developed and adapted to the AI system of software products. Therefore, for qualitative analysis, the maximum depth of investigation is bounded by the first multiple reflection that is approximately equal to the water depth. This can become a very limiting factor in shallow-water surveys.

*e.* *Beam pattern or directivity.* Experience has shown that beam pattern and transducer directivity contribute significantly to signal degradation. Sloping bottoms and rapidly dipping reflection horizons cause inconsistent reflection data through focusing and defocusing of the incident energy. Rough irregular bottoms with numerous scatterers will specularly disperse energy away from the receiving array. For quantitative analysis, minimization of the beam angle, either through beam steering or receiver focusing, will improve results significantly and will likely be incorporated in the system.

## Attributes of the AI System

In its present state of development, AI processing of seismic-reflection data provides a reasonably accurate, continuous description of bottom and subbottom marine sediment characteristics in a rapid cost-effective manner. Density can be acoustically derived to within ±10 percent of in situ conditions. Properly calibrated surveys provide Corps Districts with the following results:

*a.* Density estimate of marine sediments.

*b.* Continuous subbottom information for planning and designing dredging and sampling programs.

*c.* Estimates of the volume and type of material to be dredged.

*d.* Detailed and continuous geologic database for aiding long-term planning of future work.

If properly implemented in the project planning stages, AI provides valuable data on the distribution and extent of differing marine sediments, aids in locating optimal placements of sampling cores, and supplements previously obtained soil borings by providing continuous profile coverage of sediment characteristics between sample locations. A typical AI project flowchart and an AI data-processing flowchart are shown in Figures 15 and 16, respectively.

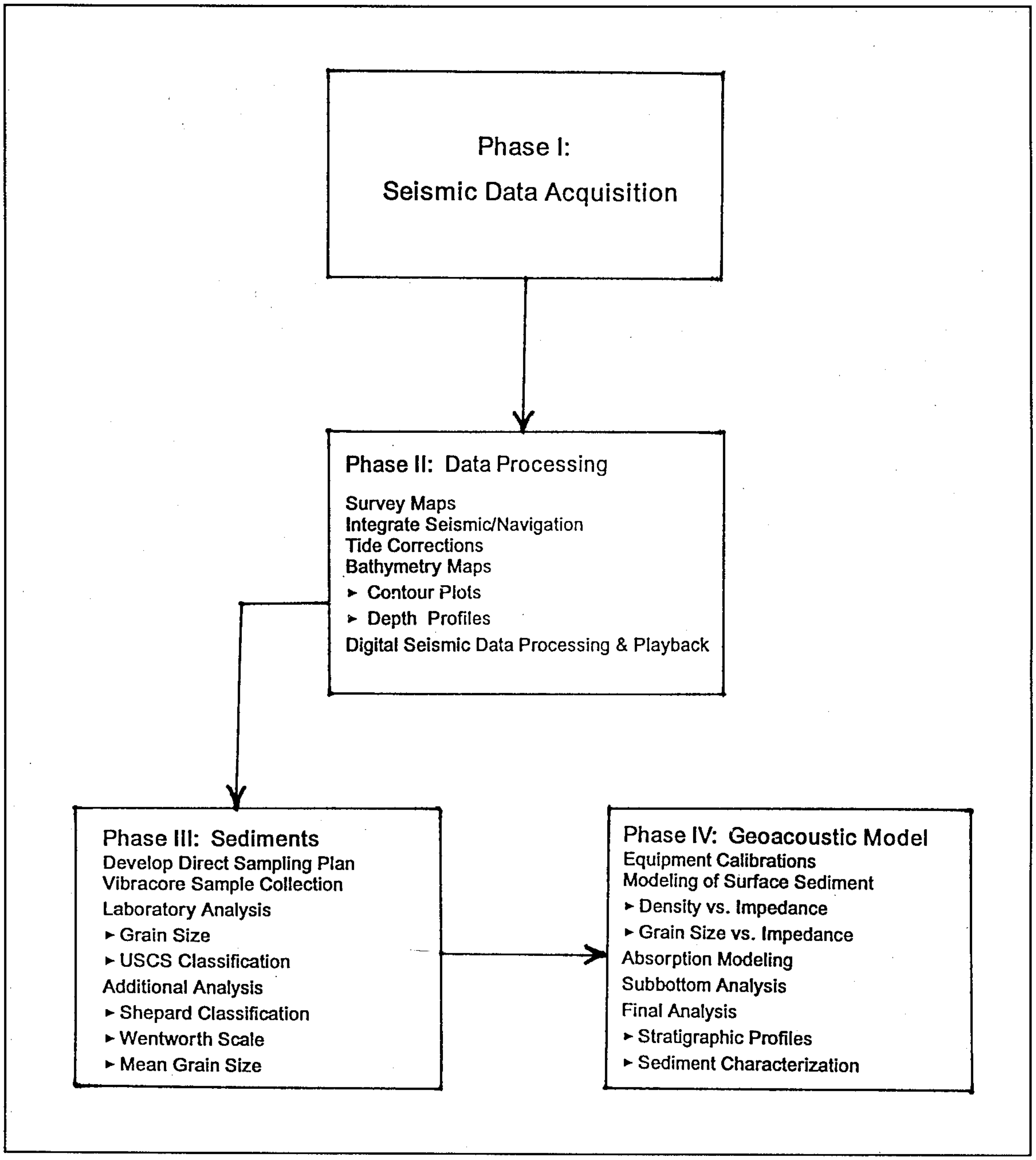


Figure 15. Typical AI project flowchart

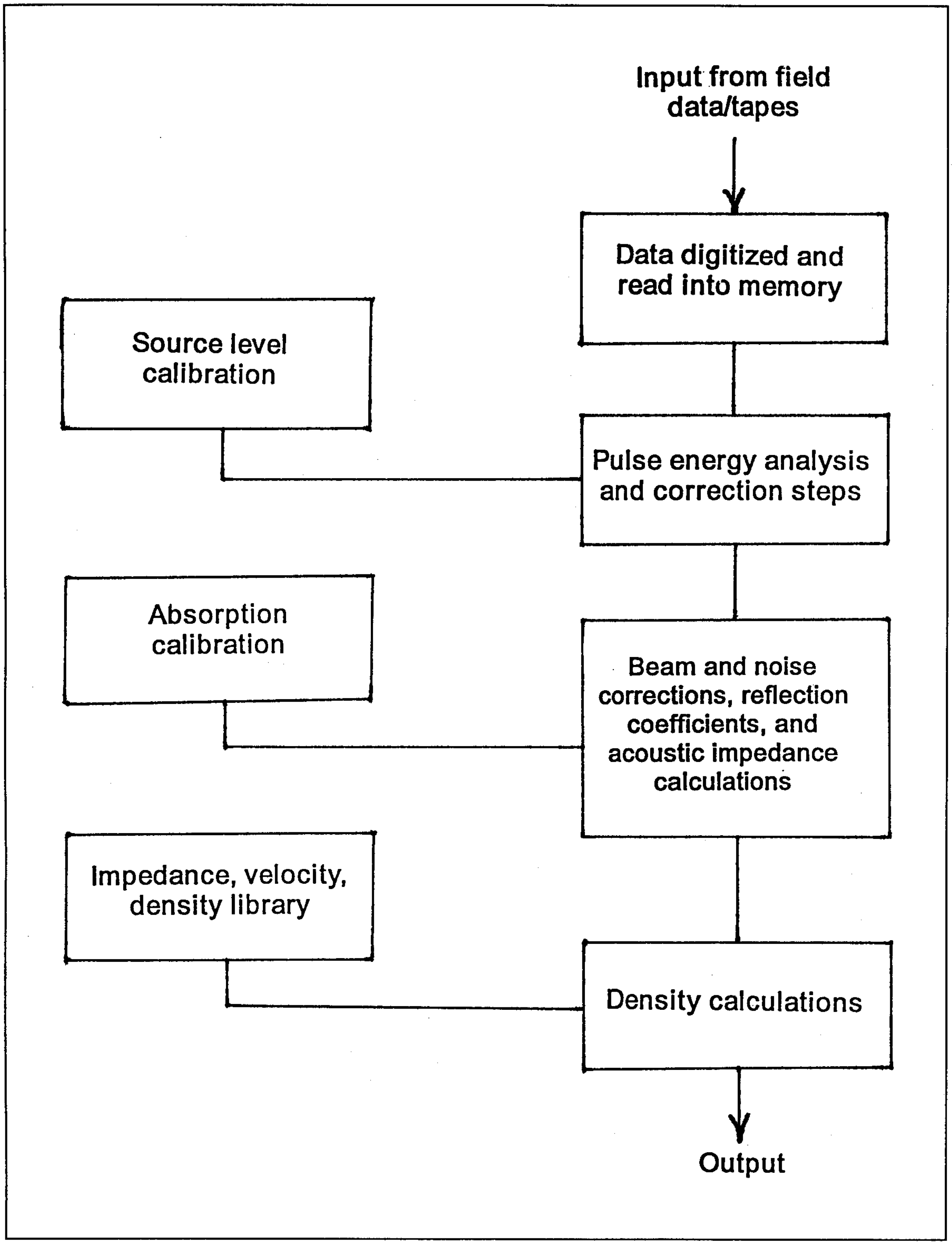


Figure 16. AI data-processing flowchart

# 6 Synopsis

This summary report of Technical Area 2 of the DRP, "Material Properties Related to Navigation and Dredging," describes the development of new instrumentation and technology that enhanced the geophysical techniques used to understand bottom and subbottom characteristics at dredging projects. Descriptors have been refined to improve communication of knowledge from the geotechnical engineers making subsurface investigations to the contractors who perform the actual dredging operations. This will significantly reduce the impact of contractor claims regarding differing and changed site conditions.

## Descriptors for Bottom Sediments to be Dredged

Descriptors have been developed so that engineering properties of bottom and subbottom sediments are either directly given or can be readily inferred for engineering applications such as dredgeability predictions. Dredgeability means the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in situ material characteristics.

### Geotechnical site-investigation strategy for dredging projects

The objective of a geotechnical site investigation for a dredging project is to obtain the most complete and accurate estimate of the location and character of the materials to be dredged that is possible within the limits of available time, money, and practicality. Spigolon (1993b) developed a strategy for a geotechnical site investigation for a dredging project.

The procedure begins with a review of all available existing information. Based on the existing information, an initial hypothesis of the geotechnical subbottom profile is developed that includes the types, configuration, and geotechnical character of the subbottom soils present in the proposed dredging prism. If the information is sufficient for the project, the site investigation is terminated. If not, then a prediction of site variability is made. If site variability is not well-known, then a geophysical survey may be appropriate. Where appropriate, continuous subbottom information is obtained by

geophysical studies using AI subbottom profiling or other suitable methods. Ground-truth correlation is required. If updated geotechnical information is now sufficient for the project, the site investigation is terminated. If the amended subsurface profile prediction is still not sufficient, then a geotechnical physical site-exploration plan is formulated. The number and location of the test sites will be dictated by site variability. At each test site, specific depths and methods are selected for sampling and testing the subbottom materials. Sampling depth may be reached by drilling or digging pits. A description and classification are made for each sample. The new geotechnical information is summarized and reviewed for consistency with the predicted profile. If the revised subbottom profile is now sufficient for the project, the site investigation is terminated. However, if more information is required, then additional geophysical and/or geotechnical sampling and testing are done. This iteration is continued until a point of sufficiency is reached.

## Geotechnical descriptors for sediments to be dredged

Soil properties data can be communicated in two basic ways: (a) raw numerical soil-identification test data, and (b) descriptors. A descriptor is defined as "a word, phrase, or alphanumeric symbol used to identify an item." Numerical test data can be communicated easily using computer database methods. However, this method does not indicate or infer dredgeability directly. Descriptive terms provide word equivalents for the numbers resulting from soil-identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information.

Spigolon (1993a), Leshchinsky (1994), and Richter and Leshchinsky (1994) have proposed consistent descriptive terms for sediments to be dredged. These descriptive terms are then related to a classification system for indicating or readily inferring the dredgeability of in situ sediments. The proposed dredging classification system places all materials in one of eight groups, each with different fundamental dredging characteristics. New-work dredging may encounter any of the eight groups. The eight groups are (a) rock and coral, (b) shale and cemented soils, (c) boulders and cobbles, (d) clean granular soils, (e) friable mixed-grain soils, (f) cohesive soils, (g) highly organic soils, and (h) fluid mud. Each of these eight groups are considered from the standpoint of four different dredgeability property evaluations: (a) geotechnical, (b) excavation, (c) removal and transport, and (d) disposal. When the eight different kinds of materials are considered from four different dredgeability property evaluations, the dredgeability of the in-situ sediments can be directly indicated or readily inferred.

## Geotechnical evaluation of the dredgeability of sediments using GEODREDG

Spigolon and Bakeer (1993) developed a KBES called GEODREDG to provide access to recorded expertise and guidance from experts in their

respective fields for the use of project planners, geotechnical engineers, and dredging estimators. GEODREDG consists of two interrelated KBES programs (GEOSITE and DREDGABL) that have been developed as part of the overall system.

**GEOSITE.** The objective of GEOSITE is to provide guidance from geotechnical engineering experts for the selection of equipment and methods for a subsurface investigation at an individual exploration site for a dredging project. It is assumed that the number and locations of the exploration sites have previously been established and that there is a general knowledge of the types of sediments to be expected at the site. GEOSITE can be used to specify the following: (a) sediment sampling methods, (b) in situ strength testing methods, considering all of the appropriate sampler/testing method combinations, (c) methods for accessing the sampling/testing depth, (d) sediment field work platforms, and (e) material identification tests.

**DREDGABL.** The objective of DREDGABL is to provide guidance from geotechnical engineering and dredging experts for the interpretation of sediment test and observation data in terms of the dredgeability of the sediment. DREDGABL is intended for use by dredging project estimators and planners working for the Corps of Engineers, dredging contractors, or dredging consultants. It can also be applied by geotechnical engineers and engineering geologists involved in dredging project site investigations to determine the sediment properties that are important for dredgeability evaluations.

## Descriptors for Rock Material to be Dredged

Site characterization is of special concern when rock is to be dredged by mechanical (nonblasting) excavation. Differing site condition claims are commonly based on the contention that rock encountered is harder to dredge with available equipment than the contractor had inferred from bidding documents. Such claims necessarily hinge on either the characterization of the rock material or the predicted performance of particular dredging equipment in excavating such material, the two being interrelated.

### Drilling parameter recorder

The drilling parameter recorder (DPR) is a generic name for systems used to record the operating characteristics of a drill rig. For site characterization work, the data record must be in direct correspondence to position in the borehole. The DPR system developed by Smith (1994) is the first of its kind to be used in the United States. In using the DPR, noncoring drilling operations over water use a tri-cone roller bit to produce a DPR record without the need for setting casing and can attain a much faster drilling rate than coring operations. Recorded drilling parameters are correlated with a small number of cored holes, usually paired with roller bit holes and produced without moving the drilling platform. Such a site-specific correlation method is especially

important where conditions are highly variable and a large number of boreholes are needed to obtain adequate site coverage.

The DPR is a data-acquisition system that monitors, measures, and records various physical parameters that reflect the operation of the drill rig, thereby producing a record of the characteristics of the formation being drilled. Eight parameters can be measured, quantified, and recorded on an analog graphical plotter and digitally recorded on tape by a microcomputer integrated into the equipment: (a) drill fluid pressure, (b) relative torque indicated by pressure to hydraulic motor for the drill string, (c) downthrust on the drill bit, (d) rate of advance (penetration speed), (e) rotation rate, (f) holdback pressure on drill string, (g) reflected vibrations (accelerations), and (h) time to drill one digitized increment of depth. DPR results correlate well with UCS.

### Point load test

The point load test (PLT) was originally proposed as a means of providing for destructive strength testing of hard rock with a portable apparatus, such that the tests produced could be correlated with UCS. Much of the costly laboratory testing requiring large stationary machines could be avoided. Smith (1994) conducted a testing program to demonstrate the applicability of the PLT for weak saturated rock found in many coastal dredging project locations and to determine any correlation of weak rock strength with UCS. It was found that correlation factors for weak saturated rock materials could easily be one half or less of published values for hard rock. A database system was developed to store, retrieve, and compare rock test data: the point load index and unconfined compressive strength (PLUCS) database system. PLUCS is an open-ended system, which presently (1995) contains data from over 400 rock tests from 10 different material sources.

## Measurement and Definition of Navigable Depth in Fluff and Fluid Mud

Thick layers of fluid mud occur at some times and at some places, especially in estuaries and navigation channels along the gulf coast of the United States. If the density and viscosity of a particular mud are sufficiently low, it is navigable; however, the margin between navigable and nonnavigable fluid-mud conditions is ill-defined, leading to unsafe navigation and/or inefficient dredging. Fluid mud causes rapid shoaling and special problems by obscuring the bottom to conventional acoustic methods for hydrographic surveying such as the fathometer. Benefits of a more precise determination of mud bottom depth include improved efficiency in maintenance operations through better definition of what areas actually require dredging or have been sufficiently dredged, and establishing more meaningful dredging priorities and scheduling.

A fluid-mud surveying system was developed by Teeter (1992a,b, 1994) and Alexander, Teeter, and Banks (in preparation) that integrated an instrumented towed sled, a conventional dual-frequency acoustic depth-sounder, and hydrographic survey positioning-control and logging components. The towed sled has nuclear-transmission density, pressure, cable tension, and multiple tilt sensors.

It was desired to have a towed sled that would furrow into fluid mud and ride automatically at the level being defined as navigable, the vertical location where a significant density transition occurs. The sled developed for channel surveys was adjusted to ride at such an elevation when towed in fluid mud. The towed sled makes physical contact with the fluid mud and serves as prima facie evidence to the navigability of the material.

Field evaluations of the towed sled for surveying navigation channels congested with fluid mud showed that the surveys are repeatable and relatively insensitive to operating conditions. Both the towed-sled concept and the hardware developed to demonstrate the concept were proven to be sound. Acoustic depth surveys are satisfactory in most areas, but can be augmented by towed-sled data to provide improved information for judging navigation conditions, dredging needs, and dredging effectiveness in those locations where navigation channels are obstructed by fluid mud.

## Rapid Measurements of Properties of Consolidated Sediments

The purpose of research by Ballard et al. (1993) and McGee, Ballard, and Caulfield (1995) was to develop a technique to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging. The study had to develop the theoretical concept, assemble the equipment, and field test a waterborne seismic AI technique for subbottom imaging. This required development of an electronic package to send and analyze acoustic signals to provide geophysical information such as density, shear strength, and grain size from the acoustic reflectivity strength of the signals. The AI technique assesses engineering properties of shallow marine sediments and provides virtually continuous coverage for delineation of both horizontal and vertical extent of those sediments. Several AI surveys have been conducted successfully.

The AI method of seismic shallow-water subbottom investigation is an enhancement of geophysical oil exploration techniques used in deep water. The AI model is an empirical technique that compensates for absorption in each layer as a function of the center frequency of a band-limited seismic trace, corrects for spherical spreading, and utilizes classical multilayer reflective mathematics to compute reflection coefficients at sediment horizons. Reflection coefficients are converted to impedances and classified according to established relationships between acoustic impedance and geotechnical

properties of marine sediments, thereby classifying lithostratigraphy. Experience to date has shown that calibrations made at a few locations within a geologic region produce the shallow seismic parameters necessary to adequately calibrate and describe the entire region.

Estimates of in situ density are derived from computed impedance values and correlated with ground-truth information. By incorporating the virtually continuous coverage of subbottom materials with digital terrain-modeling techniques, rapid and accurate computations can be made of volume and material type to be removed by dredging. Computer-generated sediment densities within the project area can be displayed in a color-coded 3-D view.

The volume of any material to be removed can be easily calculated. To estimate volume of material to be dredged, a continuous 3-D computer model of the subbottom data must be generated for each survey line. A 3-D perspective model consisting of a composite of data from all individual survey lines may be created for use in modeling proposed channel cuts, evaluating slope stability, etc. Calculating the volume of material present within a selected area is accomplished by calculating the volume of material present within the corresponding area of each profile line model.

Properly calibrated AI surveys provide Corps Districts with (a) density estimates of marine sediments, (b) continuous subbottom information for planning and designing dredging and sampling programs, (c) estimates of the volume and type of material to be dredged, and (d) a detailed and continuous geologic database for aiding long-term planning of future work.

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This report summarizes research conducted by the Dredging Research Program, Technical Area 2, "Material Properties Related to Navigation and Dredging." Goals of Technical Area 2 were to develop new instrumentation and technology for more thorough subsurface investigations at dredging projects and to refine descriptors for better communication of knowledge from Corps geotechnical engineers to dredging contractors.

A geotechnical site-investigation strategy for dredging projects was developed and descriptors were proposed so that engineering properties of bottom sediments could be readily inferred. A drilling parameter recorder and a point load test were developed to reflect operation of a drill rig and characteristics of the formation being drilled. An instrumented towed sled was fabricated which will ride automatically in a channel of fluid mud at the level being defined as navigable, thus serving as prima facie evidence of the navigability of the material. A waterborne seismic acoustic impedance system was developed to rapidly, remotely, and efficiently determine characteristics of subbottom marine sediments as they relate to dredging.

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